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PALEOMAGNETISM OF SHEMYA AND ADAK ISLANDS, ALEUTIAN ISLANDS, ALASKA

A

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PALEOMAGNETISM OF SHEMYA AND ADAK ISLANDS,

ALEUTIAN ISLANDS, ALASKA

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ABSTRACT

Paleomagnetic results are presented for Tertiary and Quaternary volcanic rocks from Shemya and Adak Islands, Aleutian Islands, Alaska. The specimens were collected and measured using standard paleomagnetic methods. Alternating field demagnetization techniques were applied to test the stability of the remanence and to remove unwanted secondary components of magnetization. The variation of the intensity of the NRM with the bulk susceptibility is discussed from the standpoint of the magnetic stability of the rocks.

Mid-Late Tertiary and Quaternary specimens satisfy several criteria of magnetic stability in igneous rocks, and derived pole positions are thought to reflect the ambient geomagnetic field at the time of the origin of the rocks. By comparison, the remanent magnetization of Early Tertiary rocks investigated is less stable and yields uncertain results in terms of pole positions.

The paleomagnetic results from the various sites are discussed with respect to the background geology of each island. Paleomagnetic pole positions derived from the results are compared with pole positions from other Tertiary and Quaternary sites in North Pacific tectonic belts.

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Base on Shemya. The assistance provided by these organizations proved invaluable and is gratefully acknowledged.

The Mobil Oil Company, through its Field Research Laboratory, generously provided a free radiometric age determination for specimens of the Adagdak volcanics, as well as for other volcanic suites along the Chain. Their help in this regard is gratefully acknowledged. Curie temperature curves for the Shemya Miocene rocks were generously provided by David Collinson of the University of Newcastle-upon-Tyne. Special thanks are due to Dr. Paul Gast of Lamont-Doherty Geological Observatory of Columbia University who provided, gratis, a radiometric age data on a unit in the Finger Bay Volcanics on Northern Adak.

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CHAPTER I

INTRODUCTION

LOCATION AND DESCRIPTION OF THE STUDY AREA

Shemya and Adak Islands are located in the Aleutian Chain, an island arc system which separates the North Pacific Ocean from the Bering Sea, and extends for some 3200 kilometers from Southern Alaska to the Kamchatka Peninsula (Fig. 1).

In the vicinity of both islands the arc in cross section is an asymmetric ridge, the crest of which contains the islands and their insular shelves. Gates and Gibson (1956) studied the submarine topography and geology of the ridge crest, and concluded that, except for modern stratovolcanic complexes, the crest is an erosion surface which truncates the top of the ridge and is the result of subaerial and marine erosion since the Mid-Tertiary, and glaciation during the Pleistocene.

The ridge is bounded on the north by the North Insular Slope, a steep, linear scarp whose base lies at a depth of about 4000 meters in the Bering Sea (Fig. 2). This feature is continuous along most of the oceanic portion of the arc and suffers a major interruption only at Bowers Bank, a projection of the Aleutian Ridge which extends into the Bering Sea. The smooth, even topography of the North Insular Slope is in marked contrast to that of the South Insular Slope, whose gently sloping surface is deeply dissected and indented by numerous sea valleys. A prominent step in the South Insular Slope, the Aleutian Bench, can be traced along most of the length of the arc. The Bench is 20-40 km wide and occurs at a depth of some 4000 meters. The

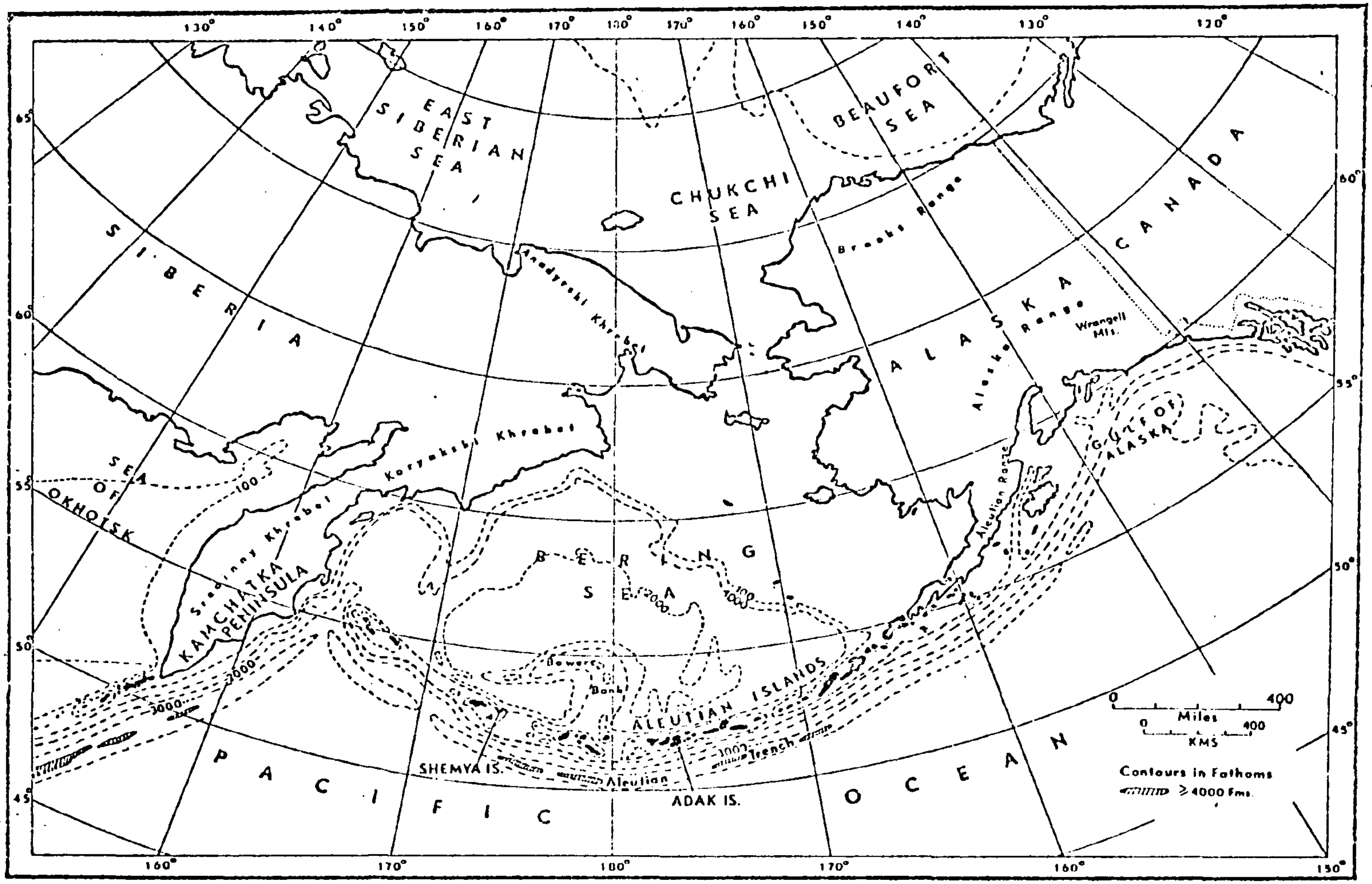


Figure 1. Map of the Bering Sea and adjacent areas showing the location of Shemya and Adak Islands.

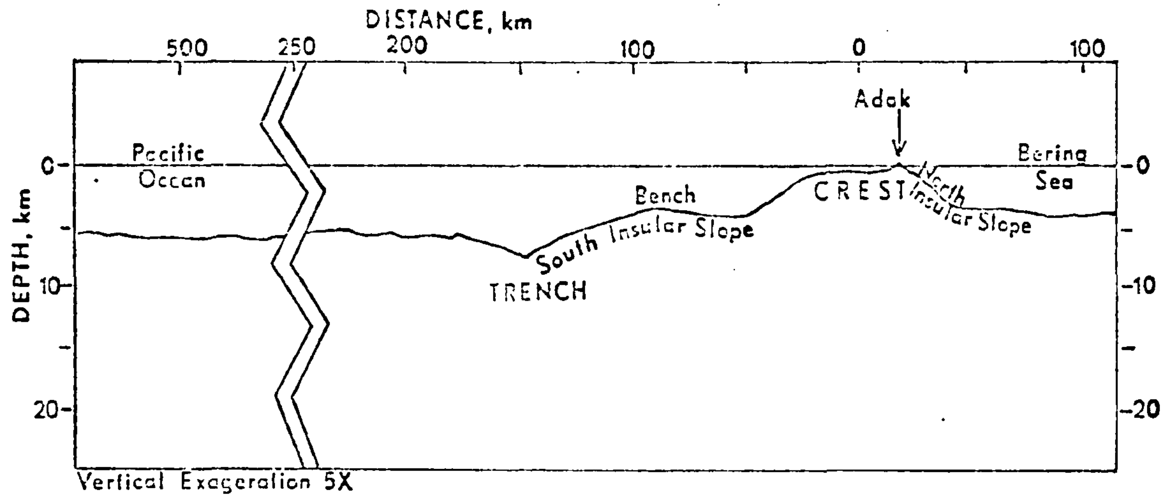


Figure 2. Topographic profile of the Aleutian Ridge in the vicinity of Adak Island showing the principal topographic provinces of Gates and Gibson (1956). Taken in part from Shor (1962).

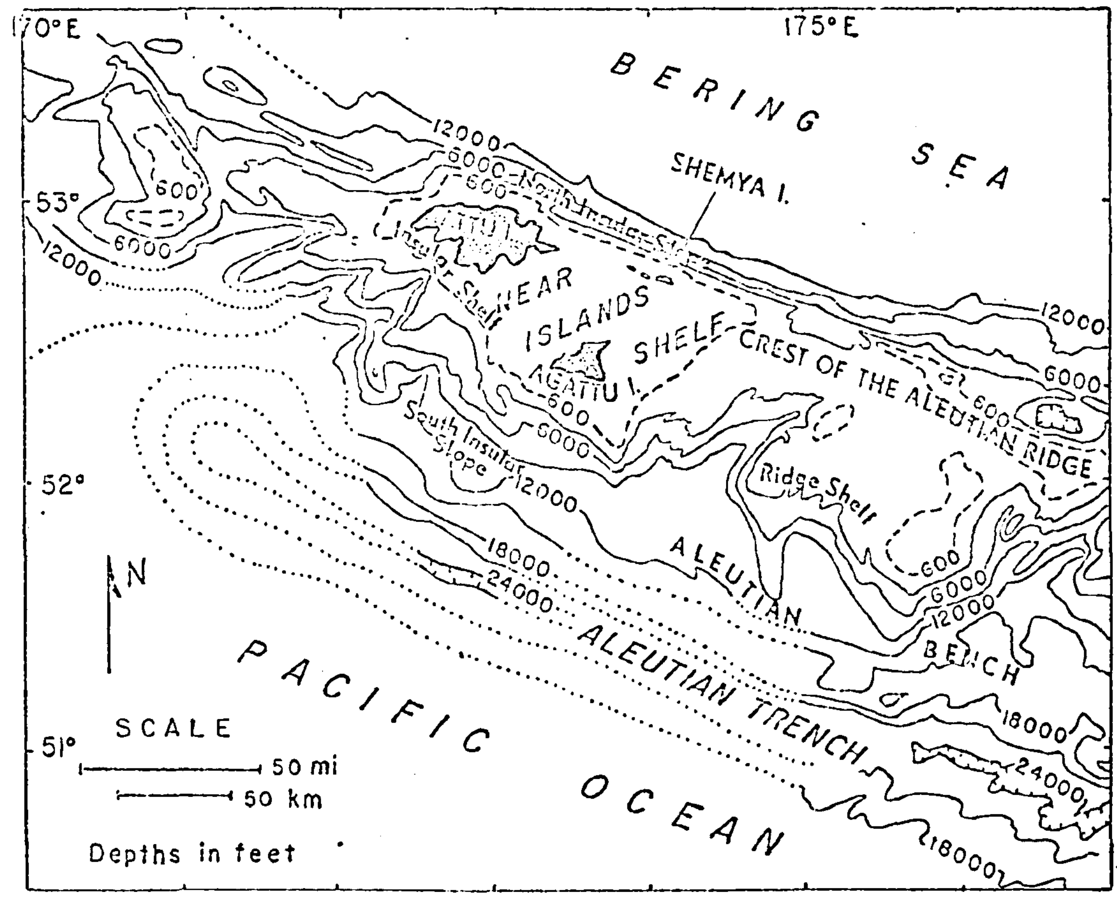


Figure 3. Index map for the Near Islands showing the location of the principal submarine topographic provinces of Gates and Gibson. Taken in part from Wilcox (1956).

Aleutian Trench forms the southern boundary of the ridge and follows an unbroken smooth curve for thousands of kilometers. The Trench is deepest in its central portion where locally its flat floor lies at depths of 8000 meters or more. South of the trench the floor of the North Pacific rises to a depth of 6000 meters [Fig. 1; Gates and Gibson (1956); Menard (1964)].

Shemya, the easternmost of the Semechi Islands, in the Near Islands Group, is situated near the northeast margin of the Near Islands Insular Shelf (Platform), at 52°43.7'N, 174°06'E (Fig. 3). The island is relatively low lying with a flat upper surface which is gently tilted to the south. The north coast of the island is characterized by steep sea cliffs which reach elevations of 80 meters. These cliffs are fringed by narrow boulder beaches which are situated on a wave-cut platform.

The Near Islands lack the Late Tertiary and Quaternary stratovolcanic complexes which characterize most of the other island groups of the Chain, hence their present elevated position is ascribed to faulting and warping of the Near Islands Platform (Gates and Gibson, 1956). The nature of the bottom sediments on the platform, the submarine topography, and the surficial geology of the islands indicate that most, if not all, of the Near Islands Platform was covered by a Pleistocene icecap (Scruton, 1953). The higher portions of Attu and Agattu have been affected by vigorous alpine glaciation. The presence of ground moraine and glacial outwash on Shemya indicates that it was covered by ice during the Pleistocene. The flat, featureless upper surface of the island, which is for the most part unmodified by fluvial erosion, suggests that the island has only recently emerged and owes its present form to marine abrasion and glaciation (Coats, 1956a).

Adak, the largest island in the Andreanof Islands Group, is situated in the central Aleutians at 51°45'N, 176°42'W. It is characterized by rugged mountain areas and broad rolling lowlands in the central and southern regions while the northern end consists of modified volcanic cones with adjacent lagoons, tidal flats and small areas of sand dunes. The extreme northern edge of the island is characterized by narrow boulder beaches backed by prominent sea cliffs.

Most of the topography of southern Adak developed as a result of intense Pleistocene glaciation during which most of the island was covered by glacial ice (Fraser and Synder, 1959). The topography of Northern Adak has been largely controlled by Late Tertiary and Quaternary volcanism originating at three centers - Mount Adagdak (Alt. 690 meters), Andrew Bay Volcano and Mount Moffett (Alt. 1292 meters). Recessional moraines on the southern flanks of the volcanos indicate that glacial ice from the south covered the major portion of northern Adak at various times. Mount Moffett has been deeply dissected, and cirques situated on its east, northeast, north, and northwest sides suggest that valley glaciers may have descended far enough down the slopes to join the ice sheet spreading from the south. Vigorous marine erosion since the last glacial maximum in the region, has carved imposing sea cliffs which, on the north sides of Mount Moffett and Mount Adagdak, are as much as 800 meters high. Wave erosion also carved a wide marine bench along parts of the northern coast which was subsequently uplifted 10 meters or so and is now exposed in the northern cliffs (Coats, 1956b).

REGIONAL GEOLOGY AND TECTONIC SETTING

General Statement

Of all the Pacific island arcs, the Aleutian island arc system is probably the least known or understood in terms of its geology, structure and evolution. Because of its remote location, inhospitable climate and lack of any economic incentive, the insular portion of the Aleutian Arc System has received little attention from geologists, geophysicists, or prospectors.

Geophysical data for the Aleutian arc system and its vicinity have been compiled and reviewed by Stone (1968), who includes an extensive list of references. In general, seismic, gravity, magnetic and heat flow profiles are widely spaced and too few in number to yield anything more than a first approximation of the deep structure of the arc system. This situation should improve rapidly as a result of geophysical work currently being conducted in the area by various government agencies and research institutions.

Geological data for the Aleutians are similarly sparse. The Aleutians were populated by various branches of the Armed Forces during and after World War II. In 1945 the dramatic eruption of Okmok Volcano on Umnak Island threatened the U.S. Air Force Base there and prompted the War Department to request that the U.S. Geological Survey undertake a program of volcano investigations in the Aleutian Chain and Alaska Peninsula. In addition to reports dealing with volcanic activity along the Chain, geologic reconnaissance maps and reports of most of the major islands were compiled. These maps and reports are contained in the U. S. Geological Survey Bulletin 1028 and are the chief sources of information on the geology of the Aleutian Islands.

Other important sources of geologic information include studies by Capps (1932); Murray (1945, 1946); Coats (1950, 1962); Gibson and Nichols (1953); Gates and Gibson (1956); Wilcox (1959); Burk (1965); Ray (1967) and Forbes et al., (i969).

Because of the lack of follow-up studies of the geology of the insular Aleutian Arc since the investigations conducted by the Geological Survey, and despite the excellent quality of their reconnaissance studies, structural and stratigraphic control is lacking over most of the Chain. Hence only a very generalized interpretation of its geologic history is possible at this time.

Seismicity and Volcanism

Like most of the Pacific rim island arc complexes, the Aleutian arc system is marked by a zone of intense seismic activity and volcanism. Stone (1968) and others have described the seismicity of the Aleutian arc system and compared it with that found in other island arc systems.

The most startling aspect of the seismicity of the Aleutian arc system is the total absence of deep hypocenter activity (550-700 km). This is in striking contrast to most of the Pacific rim island arcs and orcgenic zones and is a feature of the seismic framework of the Aleutians which has yet to be satisfactorily explained. In the eastern Aleutians and the Alaska Peninsula the seismic framework is not unlike that observed for other Pacific arc systems in terms of the distribution of shallow and intermediate depth hypocenters. In this eastern region, hypocenters associated with the structure of the arc appear to define a seismic zone which dips back under the arc and is interpreted as a major thrust fault system. The picture is somewhat less clear further to the west; however,recent epicenter data recorded at near distances suggest the presence of a similar thrust or reverse fault system (Stauder 1968a; 1968b; Murdock 1967).

The distribution of shallow and intermediate depth hypocenters under the central Aleutians can be interpreted as indicative of a large reverse fault which dips north under the arc at about 50 degrees. Further support for such a feature is found in the topography of the South Insular Slope. Here, the Aleutian Bench occurs as a relatively sharp step at a depth of some 3-4000 meters, between 50 and 75 km south of Adak Island (Fig. 2). The abrupt break in slope coincides with a zone of shallow hypocenters and the intersection of the proposed fault zone with the surface of the slope. This interpretation is also consistent with the proposal of Gates and Gibson (1956) that the bench in the western Aleutians may be the surface expression of a thrust zone. In the same context, a large, low-angle thrust zone some 100 km north of the axis of the Trench in the Kodiak-Prince William Sound area has been defined by Savage and Hastie (1966), and Stauder and Bollinger (1966), based on data from the Prince William Sound Earthquake of 1964 and its aftershock sequence.

Gates and Gibson (1956) present an interpretation of the structure of the western Aleutian Ridge based almost entirely on the bathymetry of the area that is remarkably similar to that derived from seismic evidence. They infer two northward dipping reverse faults on the south side of the axis of the ridge, one intersecting the surface in the vicinity of the trench, the other in the vicinity of the bench. They also present good evidence for the existence of a major zone of normal faults defined by the North Insular Slope of the arc. In the Western Aleutians this slope is very straight and scarp-like, and its gradient of 15° is much steeper than the 4°17' average gradient of typical continental slopes (Fig. 4).

The trench itself has long been thought to be the locus of a large northward dipping thrust or reverse fault zone. Ocean floor spreading and convection hypotheses require that island arc trenches mark zones of under-thrusting of lithosphere from the oceanic side (Oliver et al., 1969). Epicenter data indicate that the trench, as an active tectonic element, is involved not only with the structure of the arc system but also with that of the North Pacific floor (Stone, 1968). Focal mechanisms for the trench show large tensional components at shallow levels just oceanward of its axis (Stauder, 1968b). This is consistent with Shor's (1966) graben interpretation for the deep, flat-floored areas of the trench south of Adak. An extensional mechanism is thought to result from tension generated at the upper surface of a sharply curved slab of lithosphere which is being underthrust (Oliver et al., 1969). North of the axis of the trench the focal mechanisms are indicative of compressional forces.

Indirect evidence supporting the existence of Benioff-type seismic zones under the eastern and central portions of the Aleutian arc system is found in the distribution of active andesitic stratovolcanos. The

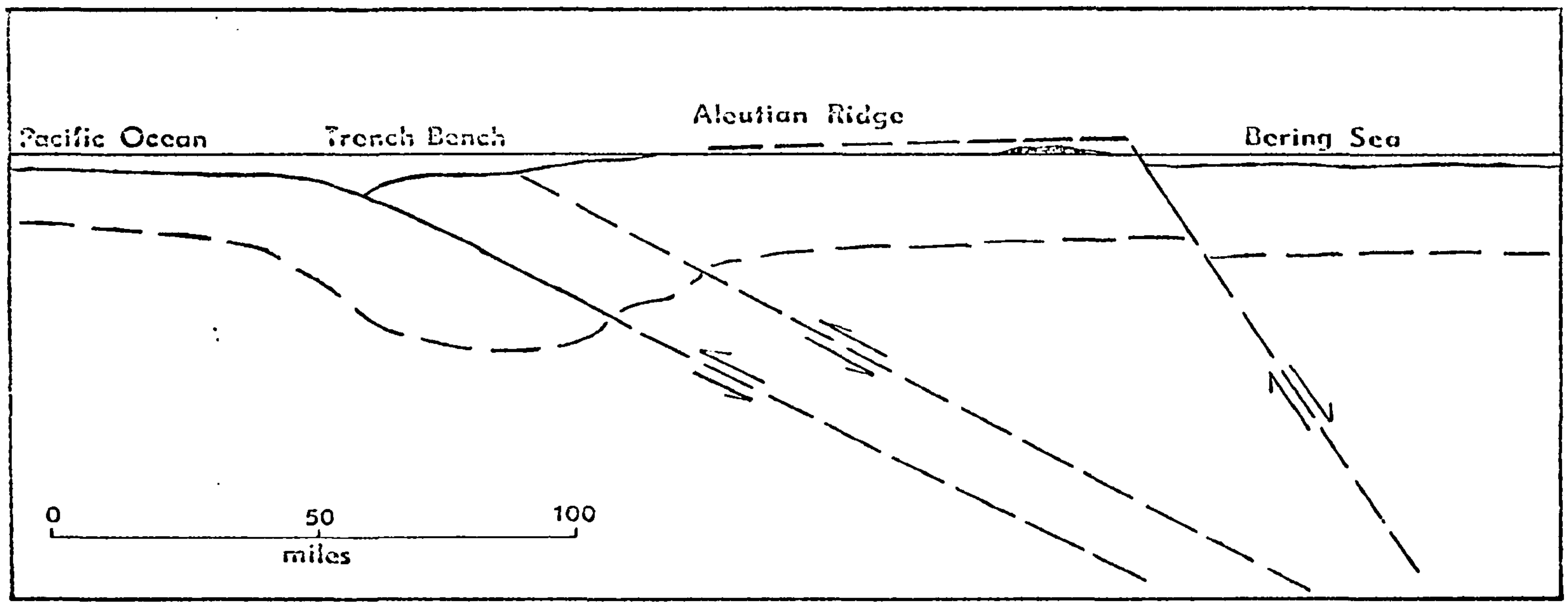


Figure 4. Diagrammatic cross section of the western part of the Aleutian Ridge and Trench. From Gates and Gibson (1956).

volcanic arc extends from Mount Spurr on the east to Buldir Island on the west and includes 76 stratovolcanic complexes, 36 of which have been active since 1760 (Coats, 1950).

The occurrence of island arc stratovolcanos over hypocenters of about 100 km depth suggests to many that it is only at this depth that eruptible magma becomes available. Coats (1962) explains the localization of the line of modern volcanos along the northern margin of the Aleutian arc by assuming that tear faults are generated at the leading edge of the overthrus plate and, unable to break through the sole or underthurst plate, propagate through the upper plate along the dipping thrust zone until depths of eruptible magma are reached.

It has been pointed out by McKenzie and Parker (1967) that andesitic volcanism in the North Pacific is associated with overthrusting of lithosphere (or, correspondingly, underthrusting of the oceanic plate). In the eastern and central Aleutians the stress system for the North Pacific, as derived from known active transform faults, is roughly perpendicular to the structural trend of the arc, and overthrusting of lithosphere occurs. In the vicinity of Amchitka Pass the structural trend of the arc undergoes a change in direction from southwest to northwest. The Pacific stress system is thus aligned more or less parallel to the structure of the arc, resulting in a change in the focal mechanisms of local earthquakes from predominantly dip-slip to predominantly strike-slip for the western Aleutians. In this portion of the arc the trench shallows perceptibly and seismic activity diminishes, becoming almost negligible between the Komandorskiis and the Kamchatka Peninsula. In terms of Coats' hypothesis, the absence of andesitic volcanism in this portion of the arc could be due to the lack of a mechanism capable of generating avenues of eruption for magma at depth.

Jordan et al., (1965) show that epicenter locations for aftershocks of the Rat Island earthquake of February 1965, tend to be confined to a rectangular zone with relatively sharp east and west boundaries. Similar distributions of aftershocks for earthquakes in the Andreanof-Fox Island region have been observed by Brazee (1965). The east-west discontinuities in epicenter density are nearly normal to the axis of the arc system and are interpreted as transcurrent faults which break the arc structure into a series of fault blocks. Each block appears to contain a major island group, although in the westernmost Aleutians relative seismic inactivity makes delineation on this basis uncertain.

Open folding, shearing, and high angle faulting characterize the local deformation on most of the islands in the Aleutian Chain. Coats (1962) summarizes lineations assumed to represent tectonic activity in the Chain and shows that the principal linear elements, chiefly faults on most of the islands trend at high angles to the structural axis of the arc. This is in good agreement with the seismic evidence cited above which argues that the Ridge is broken into several fault blocks by transcurrent faults.

The seismicity of the arc system extends northeastward into southern Alaska as far as the Alaska Range. The nature of the junction between the Aleutian Range and the Alaska Range is a matter of some speculation; however, the interpretation that it is the intersection of two distinct systems is favored by most investigators, (St. Amand, 1957; Grantz, 1966; Gedney and Berg, 1969).

Structure

As indicated above, there are only sparse geophysical and geological data pertaining to the structure of the Aleutian arc system and its vicinity. In the Aleutian Chain the useful published data from seismic experiments consist of the profiles of Shor (1962, 1964, 1966); Ewing et al., (1965); Schneider (1964) and Murdock (1966, 1967). Only the data of Shor and Ewing yield evidence regarding the nature of the crustal section above the high velocity refractor taken to represent the upper mantle.

Shor (1966) interprets the structure of the Aleutian Ridge as a narrow, uplifted section of thickened oceanic crust upon which is superimposed a chain of modern volcanos (Fig. 5). North of the ridge 5 km of oceanic crust (6.6 - 7.0 km/sec) rest irregularly on the upper mantle (7.6 - 8.9 km/sec). Under the axis of the ridge the top of the mantle is 22 - 24 km deep and the oceanic crust forms a root some 14 km thick. At this point the oceanic crust is overlain by approximately 10 km of material with a velocity of 3.8 - 5.5 km/sec, interpreted as a section of deformed basic volcanics and sediments. Immediately south of the ridge axis the situation is slightly complicated by the trench, but beyond this both the depth to the upper mantle and the thickness of the crustal section diminish, eventually becoming typical of the North Pacific.

An unreversed profile by Schneider (1964), running north and south of Adak Island, is similar in configuration to Shor's but the maximum depth of the crustal root is displaced considerably south of the ridge

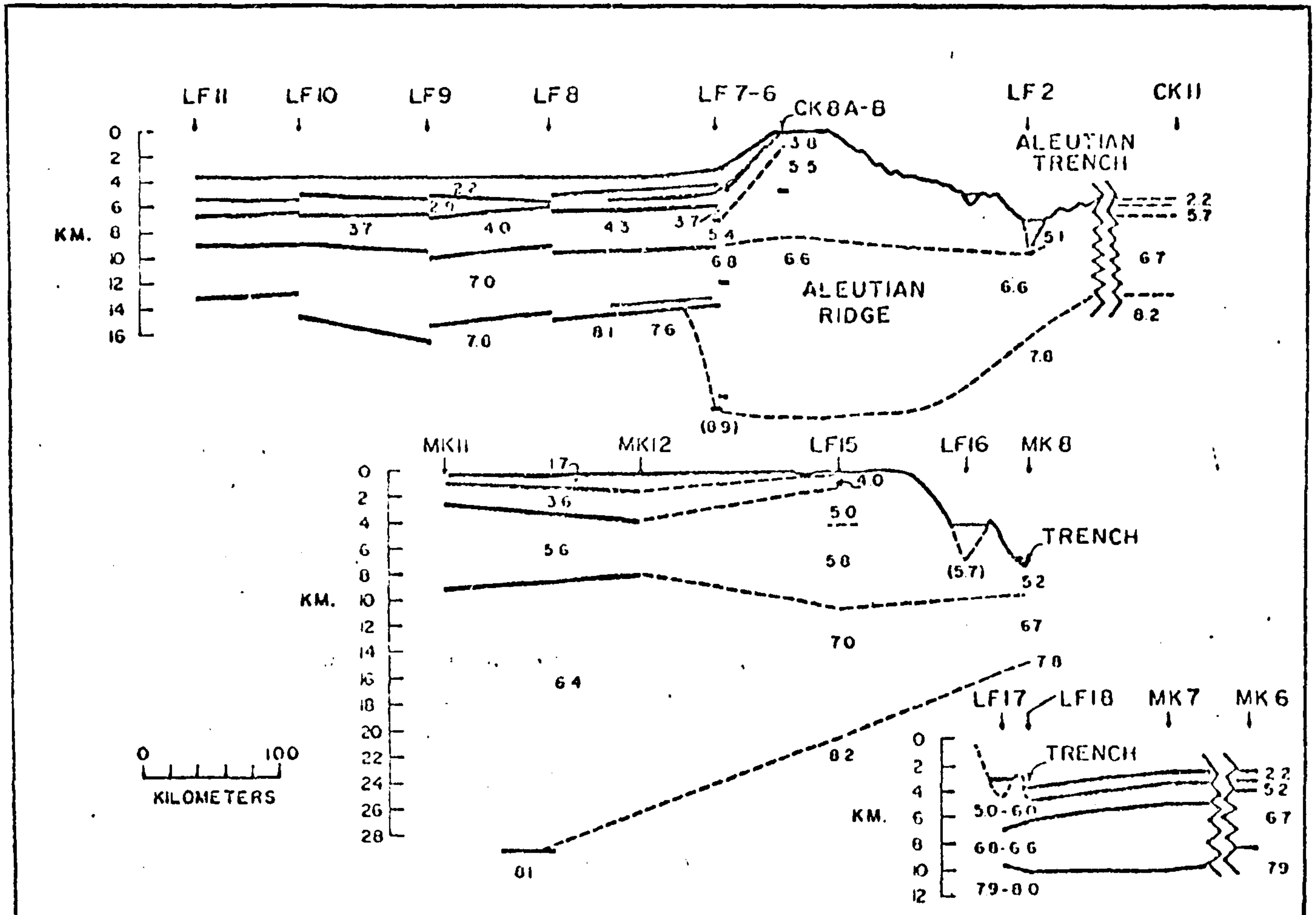


Figure 5. Crustal profile through part of the Aleutian basin (on left) and Aleutian Ridge and Trench, showing seismic layers with velocities in km/sec. From Shor (1965).

axis. It should be pointed out that between the northern margin of the arc and the Aleutian Trench, Schneider's interpretation of the deep structure is based on only a few data points, and Shor's apparently on conjecture alone.

Murdock's (1967) interpretation of the structure under the ridge is based on explosion data and epicenter studies. A profile derived from explosion data shows a crustal root extending to approximately 40 km under the ridge axis and an upper mantle velocity of 8.4 km/sec (similar to the velocity derived by Schneider but significantly higher that that of Shor). South of the maximum depth of the crustal root the mantle slopes upward until, at a point some 45 km south of the ridge axis, it is offset by a northward dipping reverse fault with a throw of about 35 kilometers (Fig. 6).

The central Aleutian profiles of Shor and Ewing show no appreciable sedimentary cover on the ridge crest. This is consistent with the interpretation that the crest represents a Late Tertiary and Quaternary erosion surface. North of the ridge the Bering Sea floor is covered by 1.5 - 2 km of horizontally stratified sediments, some of which are clearly turbidites. These are underlain unconformably by 1 - 1.5 km of a more consolidated sediment whose tilting and deformation is attributed to uplift of the Aleutian ridge and Bowers Bank. Shor's third layer consists of 4 km of consolidated sediment (?) with velocities of 3.7 - 4.3 km/sec. Near the ridge this layer blends into a thick section of material with a velocity of 5.5 km/sec. This can perhaps be interpreted as an interfingering of consolidated sediments with basic volcanics of the ridge section. The third layer may be correlative with the acoustic

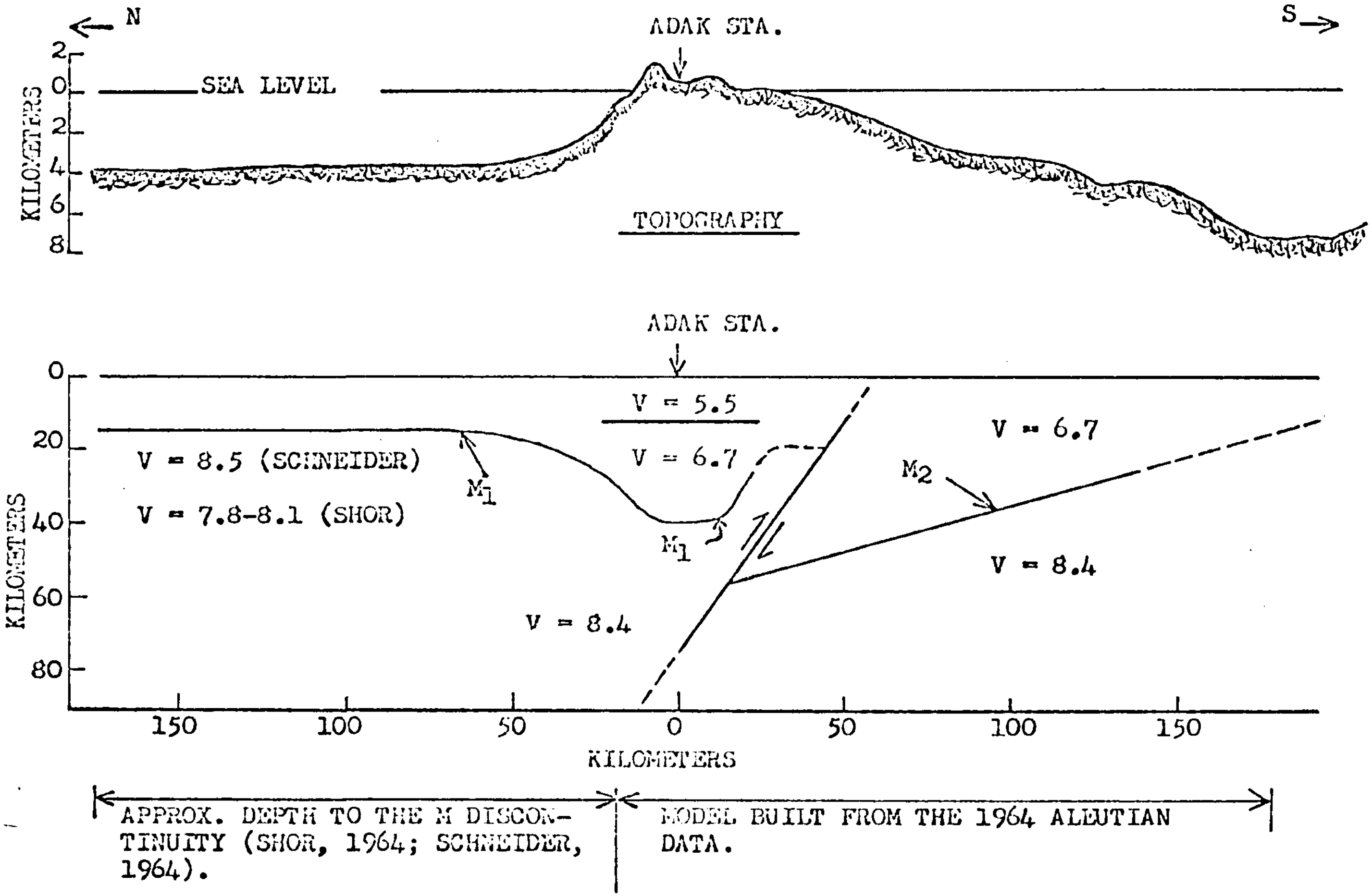


Figure 6. Crustal profile across part of the Bering Sea, through Adak, to the Aleutian Trench. From Murdock (1967).

basement complex under the eastern Bering Sea near the Pribilof Islands (Scholl et al., 1966). Recent work by Hopkins et al., (1969) on rocks dredged from the area indicates that this basement is a thoroughly lithified sequence of Late Cretaceous graywakes and siltstones. The stratified sequence overlying the basement complex consists of Early Tertiary argillite, siltstone, and calcareous sandstone, overlain by Middle or Late Miocene through Pliocene marine clastic and diatomaceous sediments. The occurrence of shallow water Miocene faunas in sediments dredged from the Pribilof Canyon at depths of 1000 meters indicate substantial vertical subsisdence of the continental margin, at least in the area southwest of the Pribilof Islands.

Available gravity data from the Aleutian arc and adjacent areas are consistent with the patterns observed in other Pacific island arcs (Stone, 1968). The profiles of Worzel (1966) and Peter (1966) show large negative free air anomalies over the trench with their minima displaced north of the trench axis. Bouguer anomalies become progressively more positive to the west. This is probably indicative of progressive increases in the proportion of basic volcanics to sedimentary material. In this context it is worth noting that the large volumes of Mesozoic sediments present on the Alaska Peninsula are not seen in the Aleutians. Late Mesozoic and Early Tertiary sections in the central and western Aleutians consist largely of basic submarine volcanics.

Most of the magnetic data in the vicinity of the Aleutian arc are from locations south of the trench in the North Pacific (Stone, 1968; Hayes and Hertzler, 1968). In the immediate vicinity of the arc the data indicate that the trench is a magnetically quiet zone. This is probably related to the removal of the material responsible for the magnetic anomalies to greater depths. The Aleutian ridge and Bowers Bank are characterized by the short-wavelength, large-amplitude anomalies commonly found in volcanic island arcs. The magnetic signature of the Bering Sea is not as pronounced as that of the North Pacific Ocean south of the Aleutian trench.

Geology

Early Marine Series

Mesozoic (?)-Middle Tertiary spilitic suites, consisting for the most part of altered pillow lavas, marine sediments, and pyroclastics, are the oldest rocks exposed in the insular Aleutian Arc. These rocks will henceforth be referred to as the "early marine series" after the terminology developed by Wilcox (1959), who mapped the series in the Near Islands. The most extensive exposures of the early marine series are found on Attu, Agattu, Kiska, Amchitka, Adak, Great Sitkin, and Unalaska Islands.

The early marine series is characterized by substantial thicknesses of cherty argillites, thin bedded cherts, and limey graywakes interbedded with basaltic and andesitic pillow lavas and flows, keratophyric pyroclastics, altered tuffs, and flow breccias. The series has been extensively invaded by plutons which range in composition from diabase to granodiorite and albite granite. Rocks of the Aleutian early marine series are similar to those of other eugeosynclinal spilitic complexes, described extensively in literature dealing with island

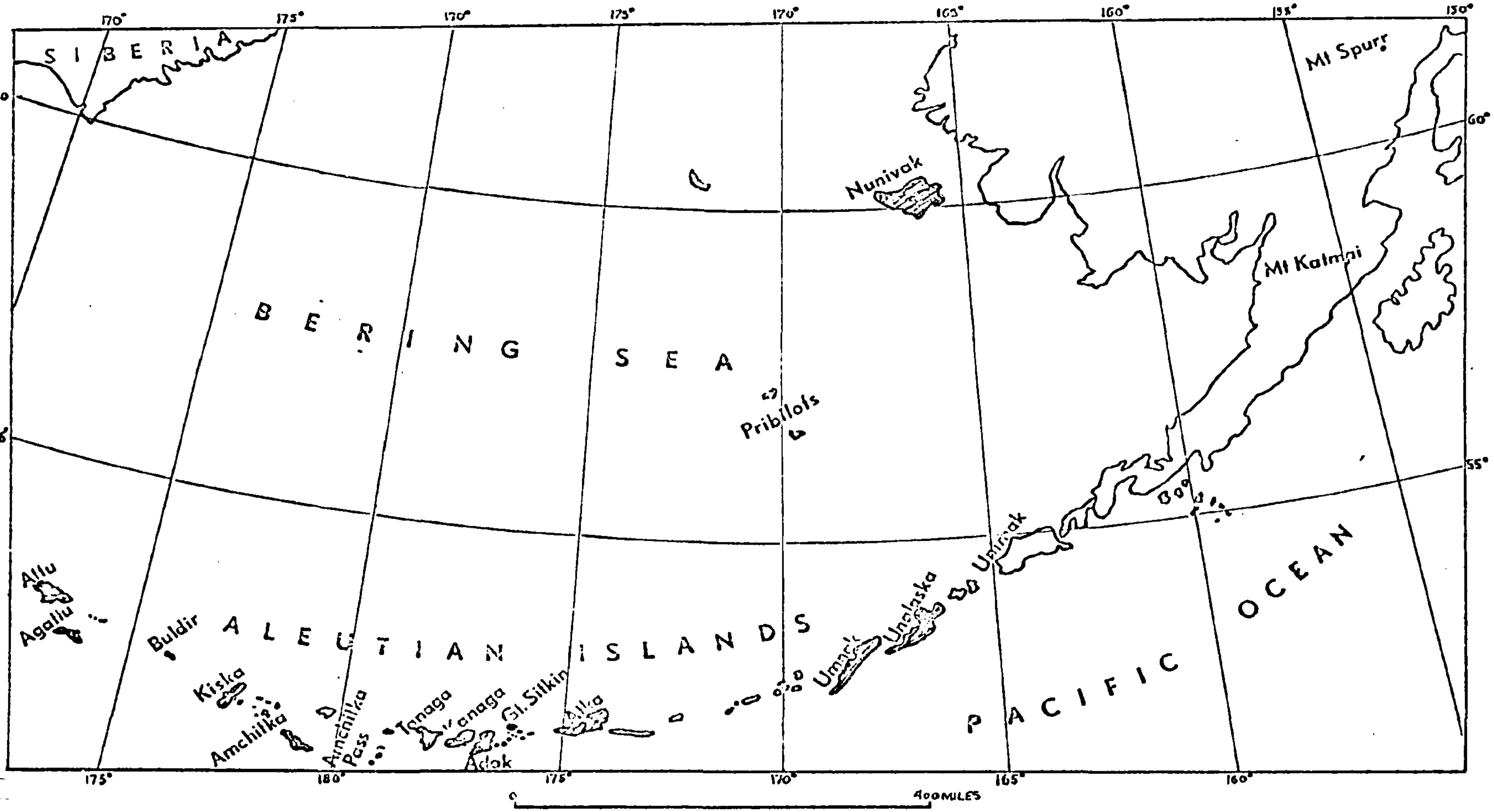


Figure 7. Map of the Alaska Peninsula and Aleutian Islands showing islands referred to in text.

arcs and orogenic belts. Only the lack of serpentinites distinguishes the Aleutian spilitic suites from typical ophiolitic associations and it is possible that serpentities are present in unexposed portions of the arc (Wilcox, 1959).

The age of the early marine series is a matter of some speculation, The section is largely unfossiliferous and stratigraphic subdivision within the series is impossible at this time. The youngest rocks cut by the Mid-Late Tertiary unconformity carry Early Miocene and Oligocene fossils . Fraser and Barnett (1959) cite the occurrence of Mesozoic fossils on Atka Island but give no details. Various Miocene fossils have been recovered from the early marine series on Tanaga and Kanaga, as well as one Echinoid species which may be as old as Eocene or Late Cretaceous. A portion of the early marine series on Northern Adak Island was originally thought to be Paleozoic in age, but further investigation of the section yielded a macrofauna of probable Eocene age and a substantial microfauna of definite Eocene age, (Scholl et al., 1969). Eocene and Oligocene Foraminifera have been found in sediments in the Near Islands as well as a few molluscs which may be as young as Miocene. In the eastern Aleutians, the age of the series is based on the fossil remains of a desmostylid sirenian - a relative of the sea cow - of probable Early Miocene age.

The tectonic and depositional environment during the formation of the early marine series is difficult to assess. Local unconformities, rapid facies changes, lensing, scouring and penecontemporaneous deformation of beds suggest a complex tectonic environment, characterized by many centers of deposition and considerable relief (Gates and Gibson, 1956). Substantial thicknesses of cherty argillites and graywackes interbedded with spilitic lavas are usually interpreted as indicative of a geosynclinal environment. Based on their study of microfossils from Northern Adak, Scholl et al., (1969), report a paleobathymetry of 1000 meters or more for the deposition of at least a portion of the Finger Bay Formation (Eocene). This is consistent with the observations of Drewes et al., (1961), who estimate the same depths for deposition of portions of the Unalaska Formation (Early Miocene) on Unalaska Island. Local unconformities within the early marine series, as well as certain fossil assemblages collected from Attu, Amchitka, Kiska, Tanaga, and Unalaska suggest that a portion of the series was deposited in shallow water. At present the most that can be said is that the available evidence suggests that substantial portions of the early marine series were deposited in a geosyncline of great lateral extent, and that the upper part of the series appears to have formed in response to uplift and deformation of the basin of deposition.

The base of the early marine series is nowhere exposed. Coats (1956a) reports gravel beds on Tanaga and Ogliuga Island which contain large numbers of smoothly rounded boulders of hornfels, hornblende gneiss, slate, schist, granulite, granodiorite, and several varieties of granite. The source of these boulders is not exposed; a possible explanation is that they may have been ice-rafted from areas of Alaska or Siberia. Inclusions ranging in composition from dunite to granite are found in shallow intrusions and flows of Quaternary age on Northern Kanaga Island of Quaternary age. Some authors suggest that these boulders are weathered-out inclusions, or the remains of metamorphosed roof pendants and border zones of large plutons such as those found on Unalaska Island. None of these suggestions can quite explain the diversity in composition and metamorphic grade of some of the boulders and at this point one must assume that either plutonic and metamorphic rocks of diverse compositions are present beneath the islands of the central Aleutians, or that a large land mass existed nearby in Mesozoic or Paleozoic time (Coats 1956a).

Low intensity alterations of the early marine series are pervasive and more than one period of igneous activity is represented. Deuteric alterations by late stage solutions, including the albitization of the calcic plagioclase of some basaltic and andesitic lavas, took place during or shortly following the eruption of extrusive representatives of the series. The sodium enrichment of these rocks took place without altering the typical extrusive textures or leaving a sodic stamp on the pyroxenes (usually common augite or a closely related variety), (Wilcox, 1959).

Sodium enrichment of spilitic lavas and pyroclastics may be related to the activity of late stage solutions which react with calcic-plagioclase to produce albite, while leaving other phases relatively unaffected, (Wilcox 1959). In an alternate hypothesis Battey (1956) postulates the primary crystallization of albite from a very wet magma with tholeiitic affinities at low temperatures. In a wet environment, which permits free diffusion of the critical cations, it is supposed that concomitant crystallization of non-sodic augite and chlorite could proceed with the crystallization of a plagioclase which loses calcium and gains sodium, finally ending up as pure albite. In either case it appears that sodium enrichment of extrusive spilitic rocks occurs during, or shortly after their deposition, through a mechanism involving 'late stage solutions'.

Keratophyric pillow lavas, dikes and pyroclastic beds are common in the early marine series, especially on Attu and Unalaska. Their compositions indicate that they were derived from non-basaltic magmas, although their sodic stamp is probably the result of the same sort of alteration mechanism as for the more mafic spilites. The development of pillow structures in siliceous lavas is perhaps indicative of a lowering of the viscosity of the magma due to incorporation of water at the time of extrusion (Wilcox,1959). Palagonitic lapilli tuffs and tuff breccias are also very common in the early marine series. On eastern Amchitka Island tuff breccias and tuffs are the most abundant rocks of the Amchitka Formation (Early Tertiary), and locally attain thicknesses in excess of 100 meters (Powers et al., 1960). The aerial extent and thicknesses of obsidian tuff breccias and lapilli tuffs on eastern Amchitka indicate that explosive submarine eruptions of great magnitude took place in that area.

The regional unconformity which truncates the crest of the ridge is one of the most striking geologic features of the Aleutian Arc. Generally, it appears to represent a significant hiatus although it probably varies considerably in age from island group to island group. It is regarded as a Mid-Late Tertiary surface of erosion formed by regional uplift, deformation and erosion of the early marine series which commenced during the Oligocene(?), or shortly thereafter.

The uplift and deformation of the early marine series was accompanied by extensive plutonic invasion. In the eastern Aleutians the series is intruded by granodioritic and quartz monzonitic bodies of batholithic dimensions. In the Central Aleutians the intrusives are granodioritic and gabbroic in composition and occur chiefly as stocks (?) and sills. The spilitic suite in the Near Islands is extensively invaded by diabase sills with less extensive masses of albite granite at a few localities. The latter may well be the product of soda metasomatism caused by the intrusion of diabase into wet sediments (Wilcox, 1959). Intrusive bodies of hornblende andesite and dacite are related in composition to the suite of stratovolcanos (Late Pliocene-Quaternary) which overlie the unconformity. A few of these intrusives, however, are at least as old as Late Miocene and probably were emplaced at the culmination of the main orogenic phase which uplifted the ridge. It is notable that intrusives of batholithic dimensions have not been recognized in the central and western Aleutians and that the more siliceous intrusives tend to occur toward the eastern end of the Chain. The above variation, if real, may be due to the proximity of the eastern portion of the Chain to areas underlain by continental crust or to differences in tectonic mechanisms, described earlier, which tend to produce andesitic volcanism in some portions of the arc and not in others.

As has already been indicated, alteration of the rocks of the early marine series is pervasive. Most of the volcanics in the series have been altered to greenstones and keratophyres by low intensity alterations including, albitization, chloritization, epidotization, silicification, prehnitization and zeolitization, during and following deposition. Superimposed on the regional alteration of the early marine series are alterations related to the uplift and intrusion of the series. These include most of the above as well as soda and potash metasomatism and sericitation near the margins of many plutons. On Unalaska some of the rocks of the early marine series in contact zones are totally recrystallized and exhibit gneissose and schistose textures, perhaps indicating forceful intrusion of portions of the batholiths.

Late Tertiary and Quaternary Rocks

Rocks overlying the unconformity consist of andesitic strato-volcanic complexes, subaerial and shallow marine volcanogenic sediments and pyroclastics, and glacial sediments. Locally, eolian deposits are found on many of the islands. The extrusive members of the various stratovolcanos located along the Chain are compositionally similar to those of other Pacific Island arc areas. The rocks range in composition from basalt to rhyolite but andesite predominates. Pyroxene and two-pyroxene andesites are the most abundant types, however, hornblende andesites are not uncommon. An accumulating amount of evidence indicates that at least portions of the volcanic arc complex have dacitic affinities (Forbes et al., 1969). Coats (1962) and Kuno (1966) note that the lavas of the Quaternary stratovolcanos in the Chain are high in alumina.

Coats (1962) presents data which illustrate the calc-alkaline nature of the Quaternary volcanics in the Aleutians. According to his hypothesis, andesitic magmas are produced in the Aleutians through the addition of water and hyperfusable materials from eugeosynclinal deposits to eruptible basaltic magmas in the upper mantle.

Major hypotheses which seek to explain the origin of the calc-alkaline series have been outlined by O'Hara (1968), who also points out the close association of high-alumina basalt with the series. He concludes that at present a mechanism involving the fractional crystallization of a wet high-alumina basalt magma under conditions of relatively high partial pressures of oxygen suffers from the fewest objections. Water again plays a critical role and is assumed to be derived from the sediments of the geosyncline.

Forbes et al., (1969) discuss the comparative composition of continental versus island arc andesites in Alaska and conclude that andesites erupted in the oceanic portions of the Aleutian Archepelago are more iron rich than those erupted from volcanos on the Alaska Peninsula. Their study suggests the possibility that Aleutian andesites may be the product of differentiation from a basaltic parent, whereas the peninsula variants may be derived from the partial melting or anatexis of lower crustal material; perhaps the quartz diorite which appears to form the subvolcanic basement under many of the volcanos of the Alaska Peninsula, (Forbes et al., 1969).

Summary of the Geologic History

Mesozoic(?) - Middle Tertiary spilitic suites consisting for the most part of altered pillow lavas, marine sediments, and pyroclastics, represent the oldest rocks exposed in the insular Aleutian Arc. Rocks of this series were deposited, penecontemporaneously deformed and altered in a geosyncline postulated to have extended from the Alaska Peninsula on the east to perhaps as far west as the Kamchatka Peninsula. The series underwent further deformation and alteration during a middle Tertiary orogenic episode. Major uplift of the section was accompanied by the extensive invasion of plutons which range in composition from gabbro to granodiorite and albite granite. The major phase of the orogeny culminated with subaerial and shallow marine extrusion of intermediate and basic lavas, deposition of sediments, and the formation of a regional Mid-Late Tertiary unconformity which has been mapped on most of the major islands of the Chain.

Rocks overlying the unconformity consist of Latest Tertiary and Quaternary stratovolcanic complexes, subaerial and shallow marine volcanogenic sediments and pyroclastics, and glacial sediments. Continued tectonic uplift of the ridge, perhaps in response to ocean floor spreading in the North Pacific and possibly the Bering Sea area, has resulted in normal faulting of the Late Tertiary-Recent sequence, and warping and tilting of the insular platforms.

The geologic history of the Alaska Peninsula is characterized by differential vertical movements following periods of plutonic intrusion. The oldest exposed rocks are Permian to Early Jurassic volcanics and marine sediments. These were intruded by granitic plutons of Jurassic age. The area was subsequently uplifted and served as a source for some 30,000 feet of Mesozoic sediments. An equal amount of Lower Mesozoic sediments was deposited in the area of the present continental shelf. Renewed uplift resulted in the formation of a major Mid-Cretaceous unconformity. Further plutonic intrusion of the Peninsula sequences, accompanied by minor structural warping, occurred during the Early and Mid-Tertiary. Severe deformation and extensive igneous activity commenced again during the Pliocene and continues to the present. The structure and geology of the Aleutian arc system in the area of the Alaska Peninsula have been well summarized by Burk (1965) and Kienle (1969), and will not be treated further in this report.

PURPOSE OF THE STUDY

A paleomagnetic research program in mainland Alaska and the Aleutian Archepelago, conducted by members of the University of Alaska's Geophysical Institute and Geology Department, was initiated in 1966. The program is primarily concerned with providing data which will be useful in the interpretation of first order tectonic features in Alaska and adjacent areas, and aid in the construction of paleogeographic maps of the region. This dissertation reports the first paleomagnetic results from the Aleutians.

The value of the paleomagnetic technique became apparent in the early 1950's. Results from rocks of many types and ages from each of the continents have been compiled, and, if it is assumed that the main geomagnetic field has always been that of a geocentric dipole, show that large scale movements of the magnetic poles with respect to the continents have occurred. It is found that the polar wandering curves for each continent are not coincident unless some sort of continental drift is invoked. Reconstructions of ancient continental arrangements based on paleomagnetic data are presented by Irving (1964), and Van Hilten (1964). Examination of the polar wandering curves for Europe and North America shows that the American curve is consistently west of the European curve by about 20°. In order to superimpose these curves one must 'close the Atlantic'. The errors involved in deriving these curves are large but the consistent separation and position of the two are virtually indisputable.

Due to rapidly accumulating evidence from other disciplines, geophysical, geological and biological, the concept of continental displacements is now widely accepted. It is the intent of investigators here to show what part Alaska and adjacent areas play in concepts of continental displacements and global tectonics. The northern portions of the North American and Eurasian continents have been largely ignored in reconstructions of relative positions of the continents throughout geologic time. The reconstructions forming a large super-continent of North America and Eurasia are well founded in theory, but unless the radius of the earth has changed considerably, a break must be established between the two continents on the Pacific side. Most reconstructions have arbitrarily placed this break in the Bering Sea or have ignored it entirely.

Carey (1958) treats this problem in depth. In his Alaskan Orocline hypothesis he details how the gross structural features of Alaska, and its present geographic position, were evolved through a combination of large lateral displacements along several megashears and a certain amount of internal bending. Typical results of the supposed bending can be seen in the curvature of the Alaska Range, the pronounced arcuate trends of the Denali, Fairweather and Castle Mountain fault systems, as well as in the dramatic changes in metamorphic trend lines in South Central and Northwestern Alaska.

Various investigations have indicated that the source of some of the Paleozoic sediments in the North Slope area of the Brooks Range was to the north, in an area now occupied by the Canada Basin of the Arctic Ocean. To explain the absence of any possible source of the sediments one must turn to either continental displacements, or to the somewhat unlikely possibility of a foundered continent. Carey's theory places Alaska south of Siberia during the Paleozoic in what is now the Bering Sea, while Hamilton (1967) has proposed that Alaska was twisted relative to the rest of North America and occupied the Canada Basin in such a way that its north coast was adjacent to the Canadian Arctic Archepelago.

Other theories place Paleozoic Alaska north of Siberia. It is regarded as unlikely that the North American block occupied such a position during the Paleozoic; however, there exists a body of paleomagnetic evidence which can be interpreted as indicating that the North American block was displaced during the Triassic and Jurassic so that by the Cretaceous and Paleocene, Alaska had drifted to a position roughly adjacent to the north coast of Siberia (Van Hilten 1964). If this is true it implies that the Alaska-American plate has undergone substantial southerly displacement during the Tertiary. Van Bemmelen (1964, 1965) implies that such a displacement may have occurred when he suggests centrifugal spreading of the Arctic Mega-Undation, which occupies the Northpole area, toward the Verhoyansk Arc, the Aleutian Arc, and the North American Shield, to account for the a-seismic Lomonosov, Mendeleev (Alpha), and Chukchi Caf ridges (Fig. 8).

Since it is not possible to detect movements along lines of latitude using paleomagnetism it is unlikely that the method could

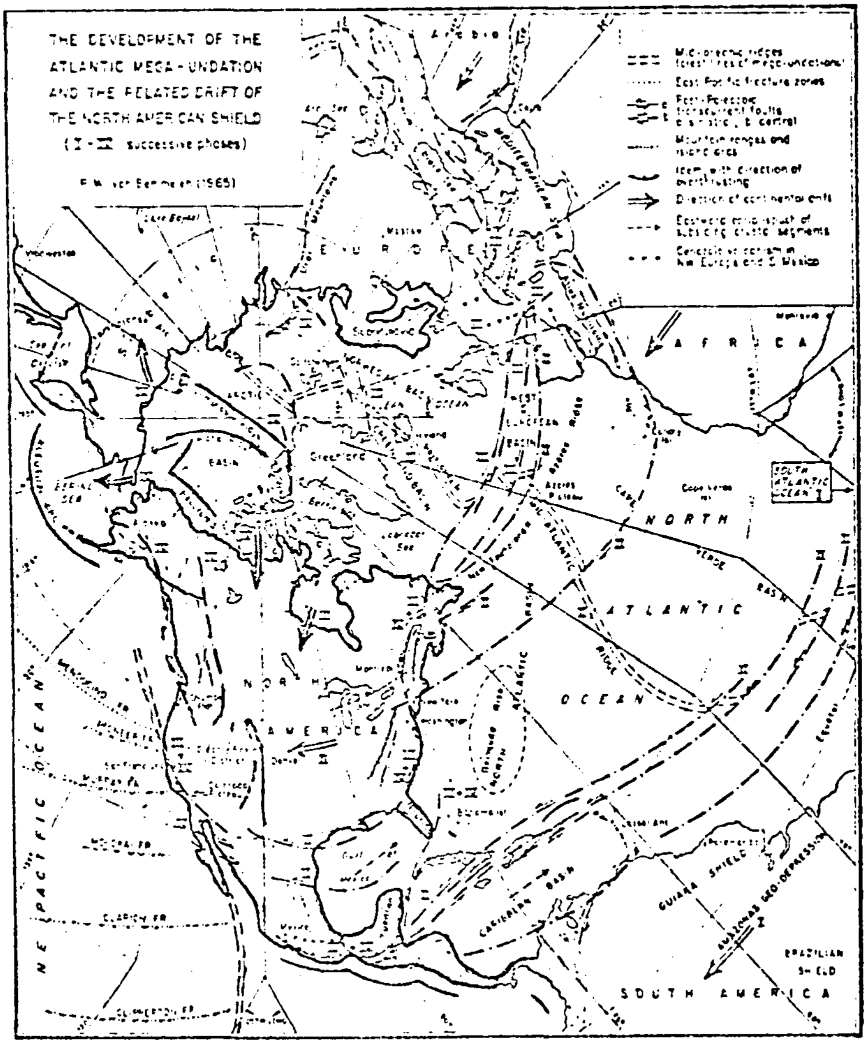


Figure 8. Geotectonic features of the northern part of the Atlantic mega-undation. After Van Bemmelen (1964, Fig. 6).

resolve whether Alaska moved out of the Bering Sea or not, as this movement would be largely along lines of latitude. However, if the movement of the Alaska-American plate has been from the north then one should be able to distinguish this, since the paleolatitudes of given sites will be north of their present position.

Carey (1958) interprets the Aleutian Arc as a nematath (a stretched submarine ridge), formed when Alaska moved out of the Bering Sea area. More recent geological and geophysical data throw some doubt on this hypothesis; however, as yet there is no direct evidence to refute it. It has also been suggested that the Aleutian Chain was formed first as a straight ridge and later bent to its present arcuate shape. Certain seismic data and features of the Arc's morphology tend to support this view. The bending hypothesis is not unreasonable considering all the current literature discussing the possible movement of large blocks or plates of the lithosphere , based on ocean floor spreading data, (see for instance Oliver et al., 1969; Isacks et al., 1968; Le Pichon 1968; Stauder 1968, and McKenzie and Parker 1967), and noting that nearly all the hypotheses generated by these investigations require the North Pacific floor to slide northwestwards under the Aleutians.

The nature of the paleomagnetic method suggests that it might provide data which could tend to support or detract from the hypotheses outlined above. Use of the technique as a tool in the interpretation of large scale structures in Alaska, and to provide evidence of possible crustal rotations in the North Pacific region was first suggested by St. Amand (1957). The paleomagnetic method demands that if a number of sites of the same age have experienced significant rotation and/or displacement relative to each other, then the movements will be seen as systemmatic differences in plots of their remanent magnetizations. Kawai et al., (1961) used this technique with considerable success in a study of the deformation of the Japanese Archipelago.

The present program for studying tectonic features of Alaska from the standpoint of paleomagnetism will attempt to establish the validity of the various bending - displacement hypotheses. The amount of bending proposed for the Alaska Range is on the order of 50 degrees, which is well above the error limits of the method. To do this for the Aleutian Arc is somewhat more marginal in view of the possibility that the arc may be segmented into several fault blocks. However, the amount of apparent bend in the vicinity of Amchitka Pass is 20 - 25°, and with enough data from the eastern and western segments of the Chain it may be possible to determine the exact nature of the change in the structural trend of the arc. This might have enormous impact on concepts of ocean floor spreading in the North Pacific. While paleomagnetism alone could not solve all the tectonic problems of Alaska and the North Pacific, it could help delinate movements in the geologic past and thus help guesses at the trends of tectonic activity, both current and future.

Ancillary results produced by paleomagnetic and associated studies include radiometric age dates, petrographic data and chemical analyses of rocks for petrologic studies, rock magnetic parameters such as susceptibility, Curie point temperatures and intensity of magnetization.

CHAPTER II

METHODS AND TECHNIQUES IN PALEOMAGNETISM

The Paleomagnetic Theory

The basic theory of paleomagnetism states that a rock, through one or more mechanisms can acquire a permanent magnetization, and that the direction and sense of this can be a reflection of the ambient geomagnetic field prevailing at the time and place of the origin of the rock. This magnetization is known as the natural remanent magnetization (NRM) of the rock, and is derived through thermal, chemical, or mechanical processes or through combinations of the same.

Thermoremanent Magnetization

Thermoremanent magnetization (TRM) is most often responsible for the NRM of igneous rocks, and is acquired when the rocks cool through the Curie temperatures of their constituent magnetic minerals in an applied field, (in nature, the ambient geomagnetic field). The acquisition of TRM can be explained in terms of Neel's single domain theory (Irving, 1964). A rock containing an assemblage of magnetic minerals, (often of more than one phase), cools through their Curie points and acquires a magnetization. Continued cooling increases the coercive force and spontaneous magnetization of the grains until, within a relatively narrow range of temperatures a rapid increase in relaxation times occurs, effectively freezing in the spontaneous magnetization.

Chemical Remanent Magnetization

Remanent magnetization produced by chemical changes in rocks, and by the nucleation and crystallization of magnetic mineral phases, is referred to as chemical remanent magnetization (CRM). Generally this term is used to embrace those types of remanence which are derived from physio-chemical reactions which take place below the Curie temperatures of magnetic minerals. The production of CRM is believed to be related to nucleation processes whereby very small grains with very short relaxation times, and hence apparently paramagnetic, increase in size until large enough for the magnetization to stabilize, i.e. for the relaxation times to become long compared with changes in the field. Grains small enough to behave as single domain particles, (0.03-0.04 microns for magnetite), have high coercivities and hence high magnetic stabilities. The character of CRM is therefore chiefly a function of volume.

Although mainly regarded as the product of falling temperatures, TRM also exhibits aspects which are best explained in terms of grain size and shape. Strangway et al. (1968) present good evidence to show that the anomalously high stability of the TRM of many lavas is in fact due to the nucleation and crystallization of small (0.02-0.05 microns) elongate grains which behave as single domain grains. These are formed at terperatures above their Curie points during auto-oxidation of the lavas.

Detrital Remanent Magnetization

Under favorable conditions of deposition, small grains of detrital magnetite can statistically align themselves along the direction of the ambient field and preserve their orientation after becoming incorporated in sediments. The remanence of certain glacial and post glacial varves has been ascribed to this mechanism, known as detrital remanent magnetization (DRM).

Viscous Remanent Magnetization

Over very long periods of time, (relative to the very short periods of laboratory observations), the intensities of primary magnetizations will decay. This effect is thought to be due to statistical flucuations in the natural thermal agitation with sufficient energy to drive an assembly of domains towards their lowest energy state. In the presence of an applied field, perhaps different in sense and direction from the original field, a new magnetization can thus be acquired at temperatures below the Curie point. This magnetic after-effect, or viscous remanent magnetization (VRM), can often obscure or obliberate the primary magnetization (say TRM or CRM). VRM can occur as a low-temperature isothermal remanence (IRM), or as a moderate temperature effect due to a small amount of heating. This could occur through burial of the rocks, or through their heating by nearby igneous activity.

More drastic secondary effects occur as a result of physiochemical alterations of the magnetic minerals at temperatures below their Curie points. For example, the iron-titanium spinels of many basic igneous rocks will, as a result of weathering at atmospheric temperatures and pressures, experience a slow sub-solidus oxidation which may lead to exsolution of hematite. During their nucleation and growth these new variants will acquire a magnetization often capable of dominating the primary components of magnetization, and which often reflects the present or recent geomagnetic field. It is therefore necessary to regard the NRM of most igneous rocks as the sum of the primary components of TRM, and the secondary components of CRM and VRM. Fortunately however, secondary components generated in the manner outlined above often reside in lower coercivity magnetic minerals, and can often be erased in the laboratory by progressive alternating field or thermal demagnetization techniques.

Method of Investigation

Specimens treated in this investigation were collected and measured using techniques which are well described in the literature, (Collinson, et al., 1967).

Collections were made on Shemya and Northern Adak Islands during the summer of 1967. Additional specimens were collected from some of the units on Adak during the summer of 1968. The specimens were collected as oriented cores of 2.54 cm diameter with a portable gasoline powered drill.

The cores were oriented with a device which consists of a slotted tube fitted with an inclinometer and a platform upon which a compass can be mounted. In practice the tube is fitted over the core and the orienting device leveled. A fiducial line is scribed along the length of the core with a bronze rod. Orientation of the core is then accomplished by recording the magnetic bearing of the fiducial line, by sightings on prominent mapped features, or with a sun compass, and with the inclinometer. The nature of the paleomagnetic method demands that wherever possible an intelligent estimate of the ancient horizontal be made for each outcrop sampled. It was possible to do this for most of the flow and sediment sequences sampled by referring to bedding planes, gravitational layering, flow banding, or similar features. Data from the four intrusive bodies sampled on Adak were reduced without structural correction. The regional dip of Shemya Island was applied to the data from the Miocene intrusive complex there.

The core specimens were sliced into 1 cm thick discs for analyses in the laboratory. The individual discs were lettered A, B, C, etc., with disc A being nearest to the top of the core, (and therefore the most affected by weathering). It was generally possible to cut three such discs from each core with material left over for the preparation of thin sections, chemical analyses, and radiometric age determinations.

The low-field bulk susceptibility of each disc was measured on a total and anisotropic susceptibility meter (Collinson, et al., 1963). The apparatus is a type of transformer bridge consisting of a pair of ferrite cores, each cut by an air gap. The cores have a pair of exciting coils wound in series, and a pair of secondary coils wound in series opposition. In the ideal situation these coils would give a zero net signal. The cores are energized by an 800 hertz oscillator. Signals recieved from the ferrites are amplified, filtered by a phase sensitive detector, and displayed on a meter. The bridge is initially balanced by moving a ferrite slug relative to the air gap in one of the cores. A sample inserted in the air gap of the other core causes a change in the reluctance of the gap, which unbalances the previously balanced a.c. circuit. The amount of unbalance is proportional to the susceptibility of the sample. The bridge was calibrated by using chemical standards of known susceptibility in sample-shaped holders.

Two methods were used to measure the directions and intensities of the remanent magnetizations of the specimens. The first employs a low-sensitivity astatic-type magnetometer which uses a pair of fluxgate magnetometer probes in place of the more usual magnet pair. The probes are oriented in opposition and connected together as a gradiometer. Calibration is accomplished by passing a known current through windings about a plastic, sample-shaped disc of accurately known dimensions. The changes in the field due to the proximity of the calibration disc (or rock sample) to the probes can then be measured directly. The sensitivities achieved with this apparatus range down to 10^{-4} emu/cm^3. In terms of the initial remanences (before demagnetization) of the Mid-Late Tertiary and Quaternary igneous rocks treated in this investigation, these sensitivities were generally adaquate.

The second magnetometer system used is a spinner type based on a design by Foster (1966). In this case the rock is rotated at 5 r.p.s. close to one of the probes of a fluxgate gradiometer pair similar to that used in the astatic magnetometer. A phase sensitive rectifier is used to filter the output signal using a reference signal obtained from a photoelectric device on the shaft rotating the sample. The amplitudes of the signals obtained with the sample mounted in several different positions of three mutually perpendicular planes are measured, and the direction and intensity of the remanent magnetization calculated from these. The absolute sensitivity of this device ranges down to 10^{-7} emu/cm^3. The spinner magnetometer was used chiefly to measure the remanence of the specimens after demagnetization.

In the technique employed in this investigation, the samples were measured for their natural remanent magnetization before demagnetization. The results were computed and plotted on a stereographic (Wulff) projection. Poor grouping of a series of rocks from one site, or gouping about the present pole, are generally indicative of unstable secondary components of magnetization. The ratio of the intensity of the NRM to the susceptibility, $\frac{Mnrm}{k}$ (the Koenigsberger or Q_n-ratio), was computed to give a general idea of the stability of the rocks. Values of about 1 or more for this ratio generally indicate that the NRM is predominantly stable. Values below 0.1 generally indicate the presence of substantial unstable components. As a general guide the ratio has practical value; however, the test must be performed with caution since low Q-ratios can arise through stable magnetizations acquired in weak fields, or through viscous decay of the original magnetization without the build-up of unstable components (Irving, 1964).

To test the stability of the magnetizations and to remove unwanted secondary components, the specimens were slowly demagnetized in a stepwise fashion by alternating magnetic fields. It is thought that by applying progressively more powerful demagnetizing fields to the sample, the least stable (i.e. those at the low coercive force end of the spectrum) components of the remanence will be removed first, leaving the components most likely to have recorded the original field. With the apparatus in use here, the alternating field applied to the specimen decays from its peak field to zero in approximately 4 minutes. The demagnetizing operations are carried out in field-free space generated by large Helmholtz coil systems in order to avoid the introduction of new magnetizations by the ambient field. Simultaneous demagnetization along all directions is accomplished by rotating the specimen around two mutually perpendicular axes.

Interpretation of Paleomagnetic Results

Any given set of paleomagnetic data can be interpreted in a number of different ways depending on the basic assumptions made. The most common assumption involved in paleomagnetic interpretation, and the one followed throughout this investigation, is that the mean geomagnetic field has always been that of a geocentric dipole. Because of the geometric relationship between the geomagnetic latitude for a dipole field and its magnetic directions on the surface of the earth, it is possible to calculate the geographic position of the axis of an appropriate centered dipole capable of producing the observed results. In light of the increasing amount of internally consistant paleomagnetic data, the dipole assumption seems well founded. Although it is very important to recognize that this assumption has been made in cases where long range correlations are involved between widely seperated sites it becomes less important for purely local interpretations; for instance, looking at the bending of a small curved feature. The results of all measurements for remanence directions were reduced and pole positions and statistical parameters calculated by an IBM 360 computor at the University of Alaska. In all cases the directions (declination and inclination) were referred to the horizontal plane at the time of formation of the rock(s) and to true (geographic) north.

Paleomagnetic results can be expressed in a number of ways. In the method used here, directions are plotted on a stereographic projection (Wulff net). Unless stated to the contrary, all directions are plotted on the lower hemisphere. Dots represent north-seeking, or "normal" directions (i.e. directions with polarities the same as the present field). Open circles represent south-seeking or "reversed" directions (i.e. directions with polarities opposite to the present field). Results of the stepwise demagnetization of selected specimens from each site are expressed on graphs which show the intensity of the magnetization (M), plotted against demagnetizing field (in oersteds), and on stereographic nets which show the effect of the demagnetization on the vector directions.

The biggest source of error in interpreting the data comes from inconsistencies in dating the origin of the remanent magnetization. There are two main sources of error; first, the geologic ages of some of the formations being sampled may be ill known, and second, the problem of determining whether or not the observed remanence dates from the origin of the rock or from a later stage in its history. Dating was achieved by radiometric means for most of the volcanic units and shallow intrusive complexes dealt with in this investigation. Thin sections of representative rocks from each site were prepared and studied to ascertain whether metamorphic events capable of extensively altering the primary magnetization had occurred, and to obtain additional information on the background geology of the areas studied. Curie point temperature curves, useful to some extent in estimating the composition of the ferromagnetic minerals of the rocks were obtained for selected samples from Shemya. In addition, chemical analyses of selected samples from Shemya were obtained to test the usefulness of the Curie point data and to establish the petrologic variations in the Miocene intrusive complex there.

The paleomagnetic technique is necessarily a statistical one, for even without errors paleomagnetic vectors would usually tend to be dispersed by secular variation. Fisher (1953), studied the problem of dispersion on a sphere and developed statistical methods which today are almost universally employed in paleomagnetic work. If N directions are observed at the same hierarchical level, then the direction cosines (l_i, m_i, n_i), of the ith direction, (D_i, I_i), a unit vector, are

$$l_i = \cos I_i \cos D_i, \qquad m_i = \cos I_i \sin D_i, \qquad n_i = \sin I_i.$$

The mean values (l, m, n) of N individual directions are then given by

$$l = \sum_i^N l_i/R, \qquad m = \sum_i^N m_i/R, \qquad n = \sum_i^N n_i/R,$$

where

$$R^2 = \left(\sum_i^N l_i\right)^2 + \left(\sum_i^N m_i\right)^2 + \left(\sum_i^N n_i\right)^2.$$

The declination, D, and the inclination, I, of the mean direction are

$$D = \tan^{-1} m/l, \quad \text{and} \quad I = \tan^{-1} n/(l^2 + m^2)^{1/2}.$$

Fisher showed that the best estimate, k, of the precision is

$$k = (N-1)/(N-R),$$

and that the radius of the circle of confidence at the 95% level

$$\alpha_{95} = 140/\,(kN)^{1/2}.$$

Mean directions whose circles of confidence do not intersect may be considered to differ significantly.

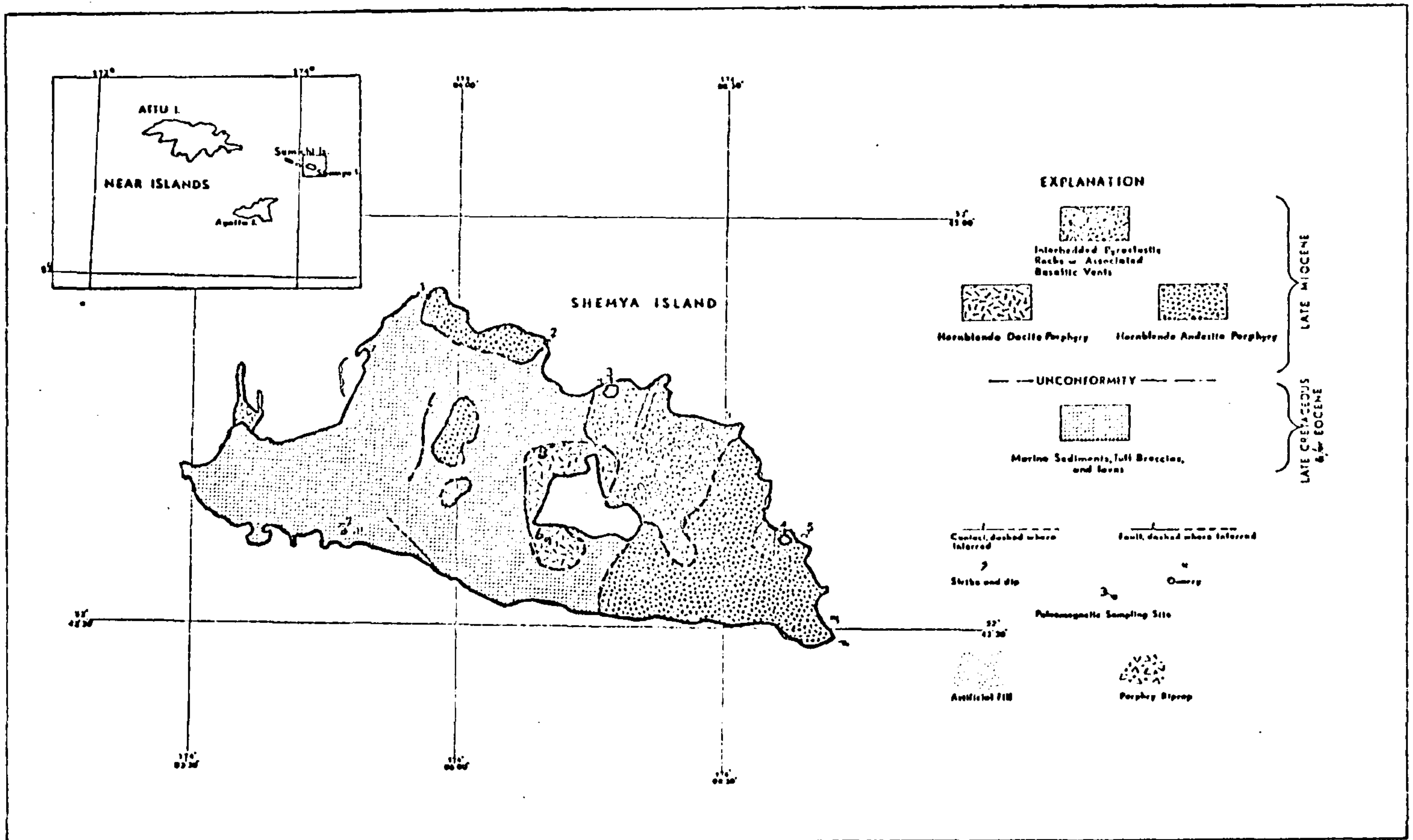
CHAPTER III

PALEOMAGNETISM AND PETROLOGY OF SHEMYA ISLAND

Geologic fieldwork and paleomagnetic sampling on Shemya Island were completed in July of 1967 by the author and Dr. D. B. Stone, Geophysical Institute, University of Alaska. A total of 8 working days were spent on the island. The profuse growth of vegetation which mantles the island limited sampling to sea cliff areas, quarries and road cuts.

The specific locations of paleomagnetic sampling sites are illustrated in Figure 9. The bedrock geology shown was compiled by F. M. Byers Jr., U. S. Geological Survey, on a map contained in Engineer Intelligence Study No. 270, (Confidential at the time of this writing). The western half of the island is underlain by marine sediments, tuff breccias, and lavas of the early marine series (Wilcox, 1959). These rocks are intruded by hornblende andesite and dacite porphyry. Portions of the early marine series and the intrusive complex are overlain by bedded pyroclastic rocks and are cut by volcanic vents of basalt and basaltic andesite. Tertiary rocks in Shemya are unconformably overlain by unconsolidated Pleistocene surficial deposits from 1 to 16 meters thick. These include sand and gravel beach deposits, peat, glacial outwash and ground moraine.

The andesite-dacite intrusive complex and the basaltic vents are Mid-Late Miocene in age. Potassium-argon age determinations on specimens from sites 3 and 6 were performed by Geochron Laboratories Inc. The specimen from site 3, a tholeiitic basalt analysed as a whole rock



Bedrock Geology after Byers ( ), and Wilcox [illegible]

Figure 9. GEOLOGIC MAP OF SHEMYA ISLAND, ALASKA

Scale 1:25,000

½ 0 1 Mile

sample, gave a date of 12.3 $\pm$ 1.5 million years. A concentrate of amphibole separated from a sample of hornblende dacite from site 6 gave a date of 15 $\pm$ 3 million years. The amount of amphibole recovered for the latter analysis was small and proved to be relatively low in potassium (0.308%). The age determination is therefore limited in its accuracy since there was not enough amphibole concentrate to perform a second argon analysis. The andesite and dacite porphyries exposed at sites 1, 2 and 5 appear to be consanguineous with the dacite porphyry exposed in the central portion of the island.

Byers considered the contacts between the intrusive porphyries and older rocks to be faulted in all cases. Good exposures of the contacts were seen only at sites 1 and 8 by this author. In the case of site 1 the usual field criteria used in defining igneous contact relations were lacking and the interpretation of the mode of occurrence of the andesite was at first uncertain. However, systematic variations of magnetic properties of andesites from this site are most easily explained in terms of an intrusive phenomena. (A complete discussion of the observed magnetic variations and their significance, submitted for publication to Earth and Planetary Science Letters, is contained in Appendix I of this report).

A steep, south-dipping contact between massive dacite porphyry and the early marine series is exposed in a quarry at site 8. Slickensides in the contact zone indicate that some displacement has occurred along the contact. Unfortunately, specimens from this site were collected parallel to the margin of the andesite. It was therefore impossible to determine if variations in magnetic properties occur as a function of distance from the contact as was the case at site 1.

It is possible that in both cases displacement along intrusive contacts took place after emplacement of the pluton(s). Alternately the paths of intrusion may have been controlled by high angle shears and faults formed in response to uplift of the ridge.

Description and Petrography of Sampling Sites

Modal analyses of selected specimens from each of the Mid-Late Miocene sites are given in Table 1. Checmical compositions and molecular norms for specimens from 5 of the 7 Mid-Late Miocene sites are given in Table 2. The description and petrography of each site follows below:

Site 1 (S60-S64). Hornblende Andesite

Five core specimens were collected from a Mid-Late Miocene hornblende andesite porphyry which is exposed in an abandoned quarry on the north side of the island. A well defined, steep, west-dipping contact between the andesite and highly sheared and deformed Early Tertiary sediments is exposed at the west edge of the quarry. The specimens were collected at intervals of 1-5 meters with S64 taken nearest the contact.

Petrography

Phenocrysts of zoned and unzoned plagioclase (An44), green hornblende, oxyhornblende, clinopyroxene, hypersthene, opaque oxides and uralite are embedded in a fine-grained felted matrix composed of plagioclase, minor alkali feldspar, amphibole, pyroxene and accessories and alteration products including chlorite, uralite, epidote, quartz, carbonate and opaque oxides. Most of the mafic grains show the effect of hydrothermal alterations which affected both the phenocrysts and matrix of the rock. The oxidation of primary hornblende and pyroxenes occurred with the rapid release of pressure associated with the mobilization of

Table 1. Model Analyses of Mid-Late Miocene Basalt, Andesites, and Dacites from Shemya Island, Alaska (Point Count Method; 1000 points)

Site[1] No.	Specimen No.	Hornblende and Oxyhornblende	Ortho-pyroxene	Clino-pyroxene	Uralite	Plagioclase	Fe-Oxides	Matrix/ Groundmass	Other
1	S64	8.8	4.9	2.1	-	35.8	5.0	43.4	-
2	S67	13.0	2.0	0.3	1.5	33.7	3.6	42.4	3.5[2]
3	S79	-	0.5	13.7	-	48.8	5.0	32.0	-
4	S88	2.8	2.8	2.4	4.1	39.2	4.2	44.5	-
5	S94-S96	8.9	1.6	0.5	2.4	38.8	3.2	44.6	-
6	S106	16.0	-	1.1	2.6	23.2	2.8	54.3	-
8	S126	16.1	-	1.1	0.4	21.4	3.0	58.0	-

[1]Sites 1 and 5: Hornblende Andesite; Site 3: Tholeiitic Basalt; Site 4: Basaltic Andesite; Sites 2,6 and 8: Hornblende Dacite

[2]Microgranitic intergrowths of quartz and feldspar (possibly resulting from accidental inclusions of graywacke).

Table 2. Chemical Composition and Molecular Norms, Mid-Late Miocene Basalts, Andesites, and Dacites from Shemya Island, Alaska

Chemical Analyses

	S-64	S-66	S-79	S-88	S-126
SiO_2	58.99	61.78	53.20	55.83	63.31
TiO_2	0.50	0.53	0.74	0.66	0.56
Al_2O_3	18.28	17.31	18.81	18.04	16.59
Fe_2O_3	3.38	3.24	2.91	2.99	2.49
FeO	1.64	1.18	4.29	3.10	1.37
MnO	0.11	0.08	0.14	0.12	0.05
CaO	6.41	5.77	8.33	7.03	6.35
Na_2O	3.88	4.15	3.46	3.77	3.99
K_2O	1.02	1.30	0.60	0.94	1.61
$H_2O(+)$	1.46	1.10	1.21	1.10	0.59
$H_2O(-)$	1.31	0.98	0.93	1.12	0.39
P_2O_5	0.18	0.19	0.17	0.17	0.25
	100.36	100.31	100.65	100.21	100.41
$\frac{Fe_2O_3}{Fe_2O_3+FeO}$	.67	.74	.40	.49	.69
$\frac{Ab+Or}{Ab+Or+An}$	.58	.64	.50	.57	.66

Molecular Norms

	S-64	S-66	S-79	S-88	S-126
Qz	13.99	16.37	3.71	7.15	17.07
Or	6.16	7.81	3.57	5.62	9.56
Ab	35.64	37.90	31.32	34.26	36.01
An	30.13	25.19	34.30	29.89	22.72
Di	0.96	2.13	4.99	3.43	5.84
Hy	8.55	6.51	17.61	15.16	5.01
Mt	3.09	1.85	3.07	3.16	2.14
Il	0.71	0.75	1.03	0.93	0.78
Ap	0.38	0.40	0.35	0.35	0.52
Ht	0.34	1.06	0.00	0.00	0.31

Analyst: H. Asari

S-64: Hornblende Andesite. Site 1
S-66: Hornblende Dacite. Site 2
S-79: Tholeiitic Basalt. Site 3
S-88: Basaltic Andesite. Site 4
S-126: Hornblende Dacite. Site 8

the melt and its emplacement at hypabyssal depths in the crust.

Magnetic oxides of the specimens exist in two distinct phases; as relatively large grains of primary titanomagnetite, and as very fine aggregates of titanomaghemite and rare limonite. The former are for the most part unaltered and only minor occurrences of exsolution lamellae on the grains were observed. Titanomaghemite appears to be chiefly associated with alteration products and may have been produced, at least in part, through the oxidation of mafic phases in the matrix.

Site 2 (S65-S74). Hornblende Dacite

Ten core specimens were collected from two small stacks on a beach platform on the north coast of the island.

Petrography

Essentially the same as above. Plagioclase is slightly less calcic (An40) and partially saussuritized. Microgranitic intergrowths of quartz and feldspar (possibly resulting from accidental inclusions of graywacke) occur commonly.

Site 3 (S75-S84). Tholeiitic Basalt

Core samples S75-S84 were collected from a basalt vent exposed in a road cut on the north side of the island. The vent cuts Tertiary volcanic sediments including lithic graywackes, breccias and conglomerates.

Petrography

In thin section the rocks exhibit a hyaloophitic texture with phenocrysts of zoned and unzoned plagioclase, clinopyroxene (chiefly augite), infrequent hypersthene, and opaque oxides situated in a groundmass consisting of devitrified brown glass, chlorites, epidote, and finely particulated opaque oxides. Primary and secondary iron-titanium spinels show minor exsolution of ilmenite (altered to leucoxene). Secondary quartz occurs infrequently as vug fillings.

Site 4 (S85-S90). Basaltic Andesite

Core samples S85-S90 were collected from dynamited working faces in a road materials quarry on the northeast coast of the island. The specimens were taken from a gray, microporphyritic hypersthene-hornblende andesite vent.

Petrography

Zoned and unzoned phenocrysts of plagioclase (An44), clino-pyroxene, oxyhornblende, uralite and hypersthene are situated in a pilotaxitic matrix composed of plagioclase, minor alkali feldspar, carbonate, chlorites, clinopyroxene, uralite, sericite and opaque oxides. Magnetite occurs as a primary accessory mineral and as an alteration product of mafic phases.

Site 5. (S91-S102). Hornblende Andesite

Core specimens S91-S102 were collected from shallow dipping columns of hornblende andesite exposed on a wide beach platform located approximately 300 meters northeast of the andesite vent at site 4.

Petrography

In thin section these rocks exhibit porphyritic textures with zoned and unzoned phenocrysts of plagioclase (An41) and oxyhornblende situated in a finegrained felted matrix consisting of plagioclase and alkali feldspar, pyroxene, uralite, clinozoisite, carbonate, prochlorite and opaque oxides. Pyroxene is not as abundant in these sections as in those from the other Miocene sites. Most of the mafics in these sections have undergone severe alteration to uralite, opaque oxides and chlorite.

Site 6. (S103-S108). Hornblende Dacite

Core specimens S103-S108 were collected from the working face of a dynamited cut which is located on the north side of the main runway on the south central portion of the island.

Petrography

Phenocrysts of zoned and unzoned plagioclase (An45), oxyhornblende, uralite, and highly altered clinopyroxene, are situated in a fine-grained felted groundmass consisting of plagioclase, alkali feldspar, quartz, clinopyroxene, uralite, prochlorite, clinozoisite and disseminated opaque oxides. Inclusions of large broken feldspar fragments and glomeroporphyritic plagioclase clusters are common in these rocks.

Site 7 (S109-S123). Graywacke and Palagonitic Tuff Breccia

Fifteen core specimens were collected from a quarry located near the southwest coast of the island. The quarry exposes a section of tuffs, graywackes and mudstones. The section strikes east-west and dips 55 north. It is thought to represent part of the early marine series.

Petrography

Sections S109 and S110 are calcareous graywackes. In thin section they exhibit clastic textures with fine and very fine grains of plagioclase, pyroxene, hornblende, quartz and volcanic rock fragments (consisting of plagioclase, pyroxene, and alteration products) situated in a very fine matrix consisting of epidote, calcite, chlorite and disseminated opaque oxides.

Specimens S111-S123 are palagonitic lithic tuff breccias. Volcanic rock fragments and phenocrysts of plagioclase and pyroxene are situated in a matrix composed of devitrified brown glass, palagonite and various alteration and secondary minerals. Microvesicles filled with zeolites, calcite and chlorite (?) are common in the glassy matrix of the rock. Three types of volcanic rock fragments were recognized in these sections:

1. Fragments rich in volcanic glass and palagonite, deep brown to black and orange in color, bearing phenocrysts and glomeroporphyritic aggregates of plagioclase, pyroxene and magnetite.

2. Hyalopilitic aggregates in which devitrified glass occupies the interspaces between phenocrysts and microlites of feldspar and magnetite grains.

3. Fragments which consist of felted aggregates of plagioclase, opaque oxides and altered mafic grains.

Site 8 (S125-S132). Hornblende Dacite

Core specimens S125-S132 were collected in a large quarry located in the north central part of the island.

Petrography

Essentially the same as S103-S108 (Site 6).

Paleomagnetic Observations I

Directions of Remanent Magnetization, Mid-Late Miocene Rocks

The results of the measurements of rocks from Mid-Late Miocene sites are illustrated in Figs. 10-16. These data are summarized in Tables 3 and 4 which also give pole positions and associated statistics for the respective sites. In Figs. 10-16 all directions are plotted on the lower hemispheres of the stereographic nets. Dots represent north-seeking or "normal" directions (i.e. directions with polarities the same as the present geomagnetic field). Open circles represent south-seeking or "reversed" directions (i.e. directions with polarities opposite to the present field). Circles of confidence at the 95% level are shown round the mean direction for each site.

The proportions of soft (low-coercivity) and hard (high - coercivity), components of magnetization have been estimated from the demagnetization curves of pilot specimens from each site. Often soft components are the result of the aquisition of secondary components of magnetization by physiochemical processes. They can also be due to components of viscous magnetization or isothermal magnetizations acquired in the direction of the ambient field. However, it can be shown that primary low-coercivity components can be generated during auto-oxidation of igneous rocks at temperatures near the Curie points of most ferromagnetic minerals. Substantially stable primary components of TRM in igneous rocks are generally indicated by directions which remain relatively fixed after demagnetization of the rocks in high alternating fields. For a detailed discussion of the reliability of paleomagnetic observations and magnetic stability criteria, the reader is referred to Chapter Five of Paleomagnetism and Its Application to Geological and Geophysical Problems by Irving (1964). [A brief description of Figs. 10-16 follows below.]

Site 1

The character and variations of the magnetic properties of andesites from site 1 are discussed in detail in Appendix I of this report. The mean site direction of remanent magnetization did not change significantly after demagnetization in alternating fields of 500oe (peak), (Fig. 10a, d). The demagnetization curves indicate the removal of soft components of magnetization in fields of 250-500oe (Fig. 10b). Although hard components make up only 5-15% of the remanent magnetization of the specimens, over 50% of the total magnetization is considered to be of primary origin. The intensity of magnetization of each specimen varied as a function of distance from the margin of the andesite and peak alternating field. In fields above 500 oe the directions of specimens, especially those nearer the contact, became dispersed (Fig. 10c).

Site 2

Most of the remanence of specimens from site 2 appears to be primary. Direction are reversed in polarity and remain relatively fixed after demagnetization in high alternating fields (Fig. 11a, c,d). Soft components comprise some 60-70% of the total remanence and were removed in fields of 500oe (peak), but no initial increase in intensity was noted, as would have been the case if a strong secondary component had been acquired in the present earth's field. (Fig. 11b)

Site 3

Directions of remanence at site 3 shifted only slightly after demagnetization of the specimens in peak fields of 500oe (Fig. 12a, d). Most of the magnetization of these specimens appears primary and the directions of the pilot samples remained relatively fixed after demagnetization in fields of 750oe (Fig. 12c). Soft components were removed in peak fields of 250-500oe (Fig. 12b).

Site 4

Specimens from the andesite vent at site 4 have reverse polarities. Sizeable soft components were removed in peak fields of 250-500oe (Fig. 13b). Hard components comprise 10-20% of the remanence of these specimens. The mean site direction of remanent magnetization did not shift appreciably after demagnetization of the specimens in peak fields of 500oe although the scatter about the mean increased slightly (Fig. 13a,b). The initial increase in intensity after demagnetization at 50oe (peak) is due to the removal of a secondary component (probably acquired in the present geomagnetic field) opposite in polarity to the dominant magnetization of the rock.

Site 5

Andesites from site 5 also show reverse polarities. The mean site direction shifted after demagnetization in peak fields of 250oe (Fig. 14a,d). The inclination of the mean direction remained relatively constant, however, the declination rotated approximately 120° from the southeast to the northeast quadrant. Relatively large soft components of magnetization were removed in alternating fields of 250-375oe (peak). A secondary component with a normal polarity was removed in a peak alternating field of 50oe (Fig. 14b). Hard components of magnetization account for approximately 10% of the total remanence of these specimens. In alternating fields above 500oe the dispersion of vector directions increases considerably (Fig. 14c).

Sites 6 & 8

Rocks from sites 6 and 8 exhibit very stable remanences. The directions of pilot specimens from these two sites did not shift after demagnetization at 1000oe (peak). Mean site directions at the respective sites also remain fixed after treatment of the specimens in high alternating fields (Figs. 15 and 16). Soft components in specimens from site 6 were removed after treatment in fields of 500oe (peak), Fig. 15b). Most of the remanence appears to be primary. Initial intensities of specimens from site 8 were somewhat lower than those observed in specimens from other Miocene sites. This may be due to the presence of only very minor secondary components; as indicated by the uniform demagnetization curves for pilot specimens S131 and S132. Hard components of magnetization appear to comprise nearly all of the total remanence of site 8 specimens.

Late Cretaceous or Eocene Rocks

Site 7

NRM directions of specimens from site 7 are widely dispersed (Fig. 17a), and, with the exception of S109 and S110, discs cut from the same core did not exhibit internal consistency. The scatter of directions decreased considerably after the specimens (2 discs per core) were treated in alternating fields of 375oe (peak), (Fig. 17d). The initial intensity was very low (relative to other sites on the island) and hard components comprise only small percentages of the total remanence, (Fig. 17c). In many specimens, a secondary component opposite in polarity to the dominant remanence was removed in peak fields of 50oe. The mean site direction, pole position, and associated statistics are shown for site 7 in Table 4.

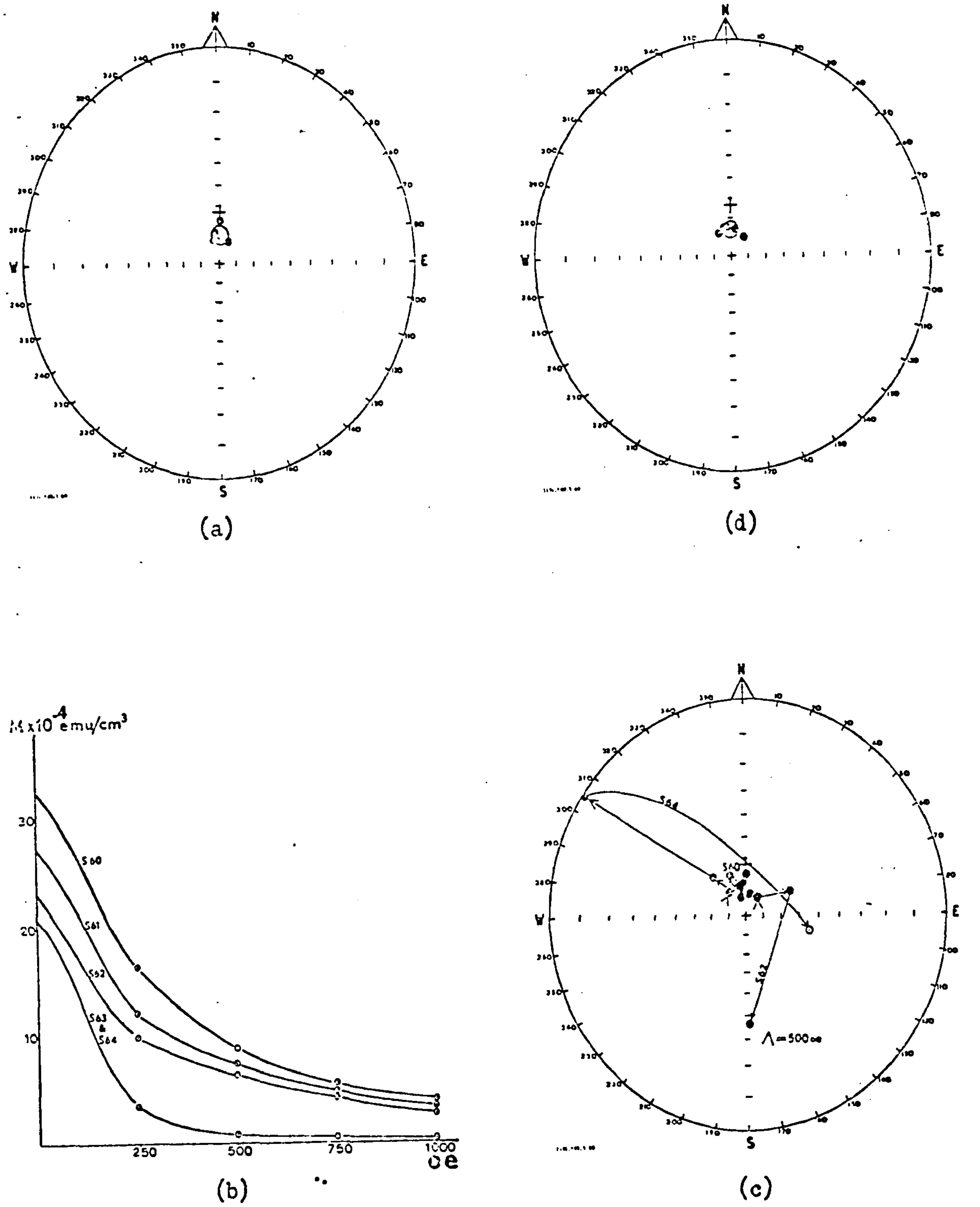
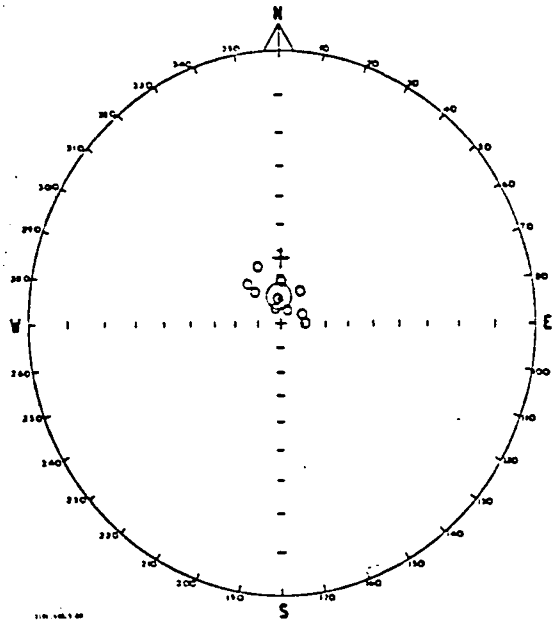
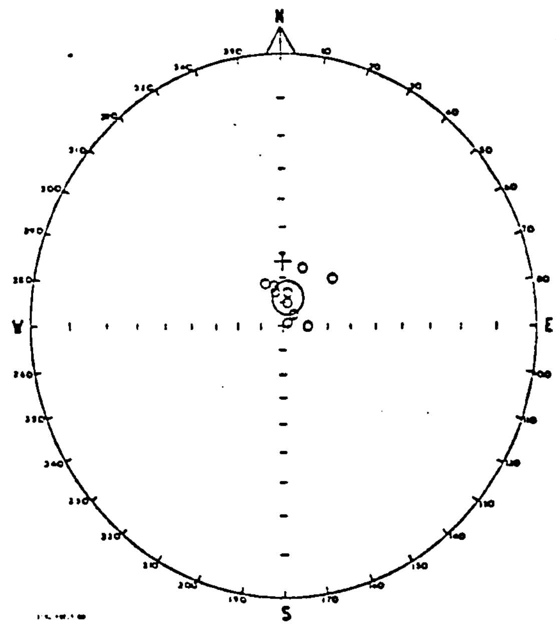


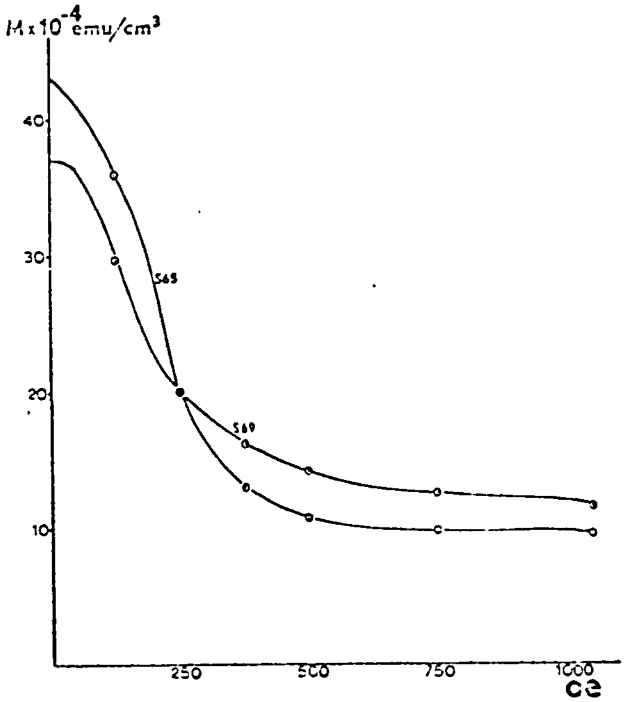
Figure 10. Directions of magnetization and effect of alternating field demagnetization in andesites from Site 1, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vectors during treatment in alternating fields. (d) Directions of magnetization of Site 1 andesites after treatment in alternating fields of 500 oe. The (+) indicates the direction of the present axial dipole field.



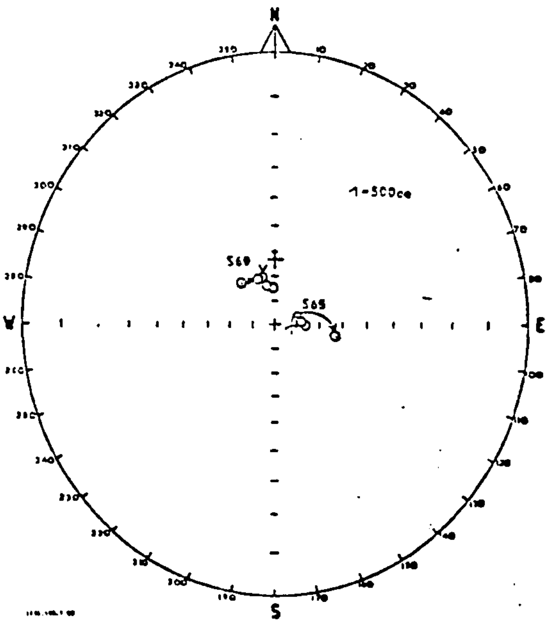
(a)



(d)



(b)



(c)

Figure 11. Directions of magnetization and effect of alternating field demagnetization in andesites from Site 2, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vectors during treatment in alternating fields. Directions of magnetization of Site 2 andesites after treatment in alternating fields of 500 oe (peak). The (+) indicates the direction of the present axial dipole field.

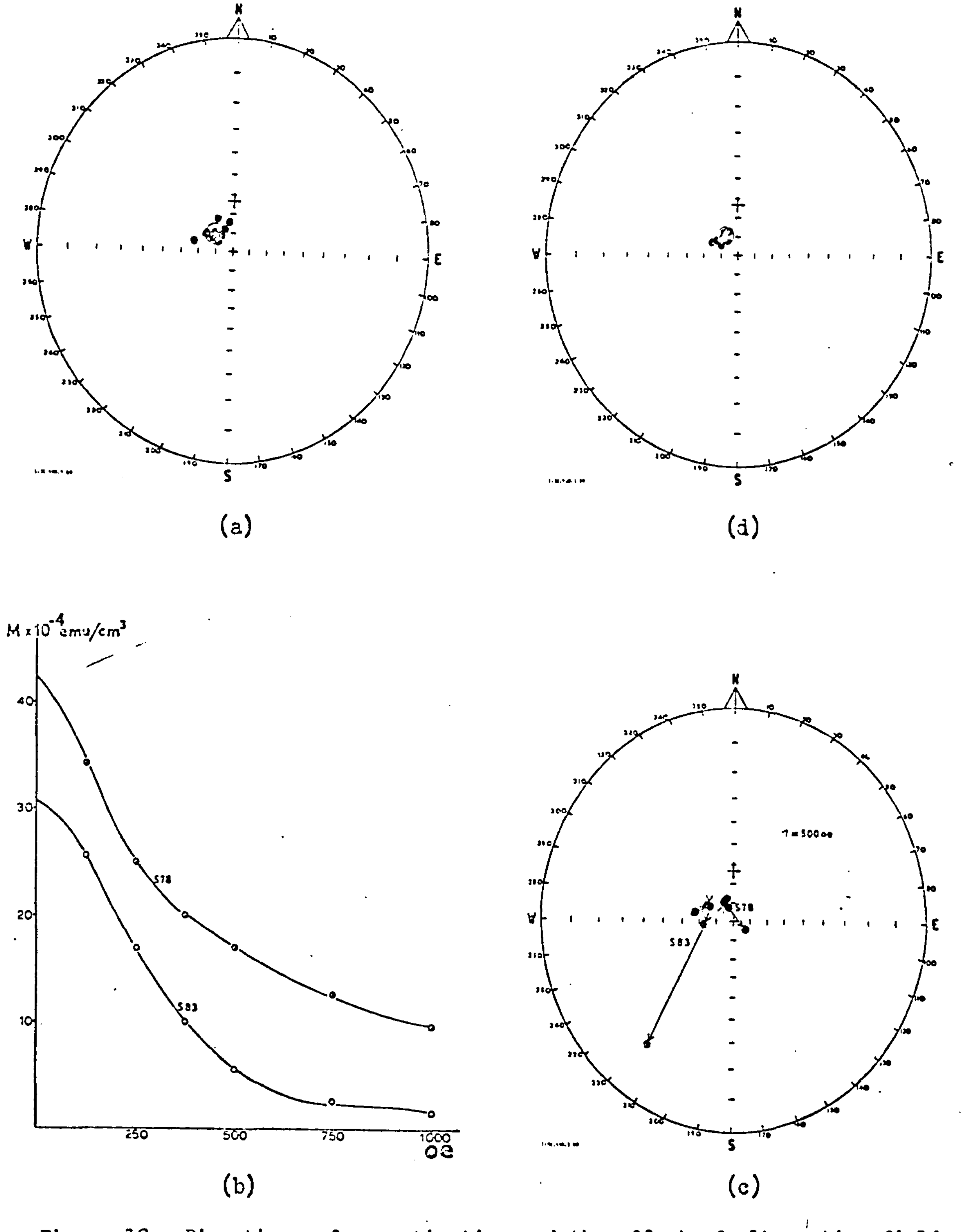


Figure 12. Directions of magnetization and the effect of alternating field demagnetization in basalt specimens from Site 3, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vectors during treatment in alternating fields. Directions of magnetization of Site 3 basalts after treatment in alternating fields of 500 oe (peak). The (+) indicates the present axial dipole field.

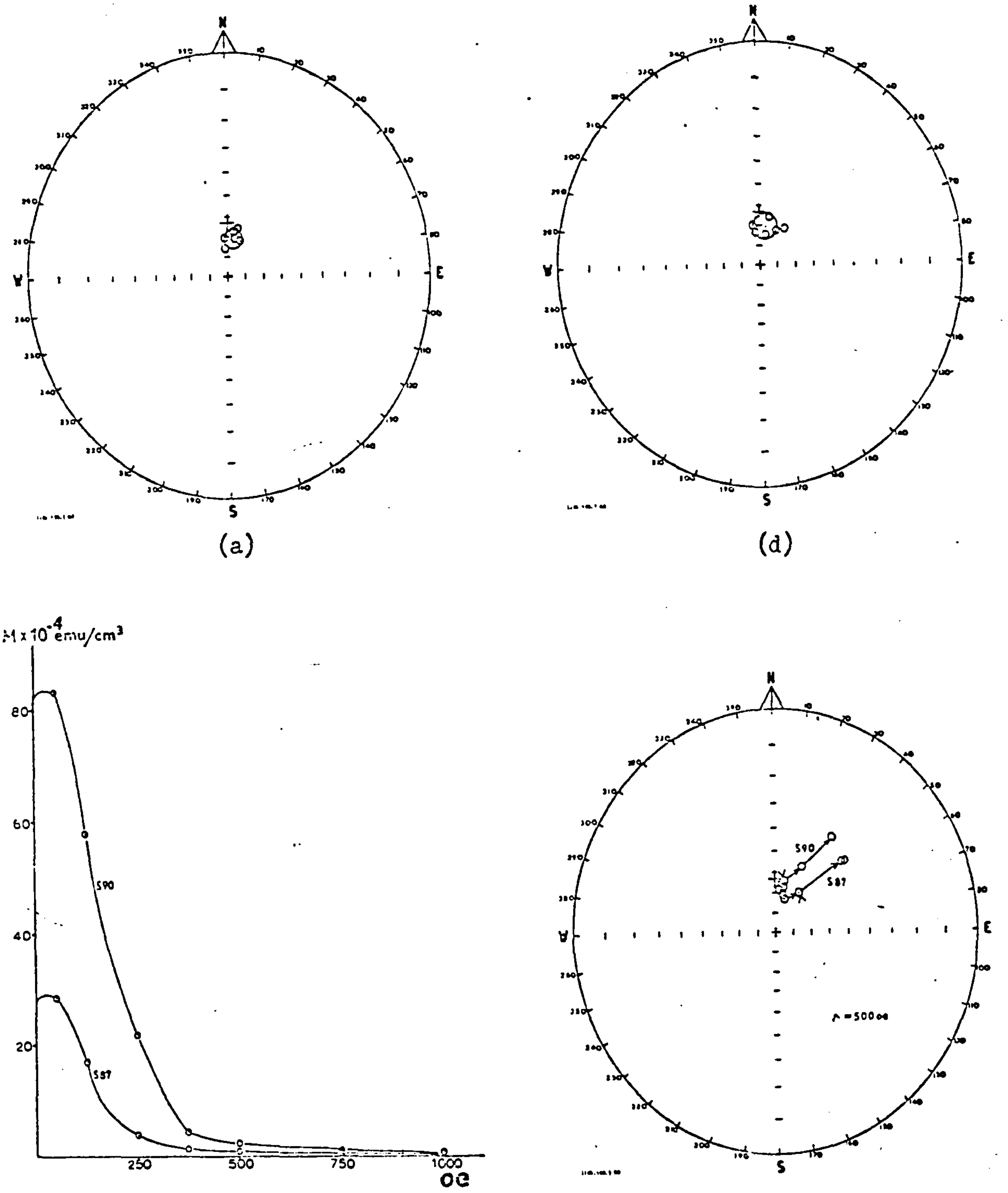


Figure 13. Directions of magnetization and effect of alternating field demagnetization in basaltic andesites from site 4, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vectors during treatment of the specimens in alternating fields. (d) Directions of magnetization of Site 4 andesites after treatment in alternating fields of 500 oe (peak). The (+) indicates the direction of the present axial dipole field.

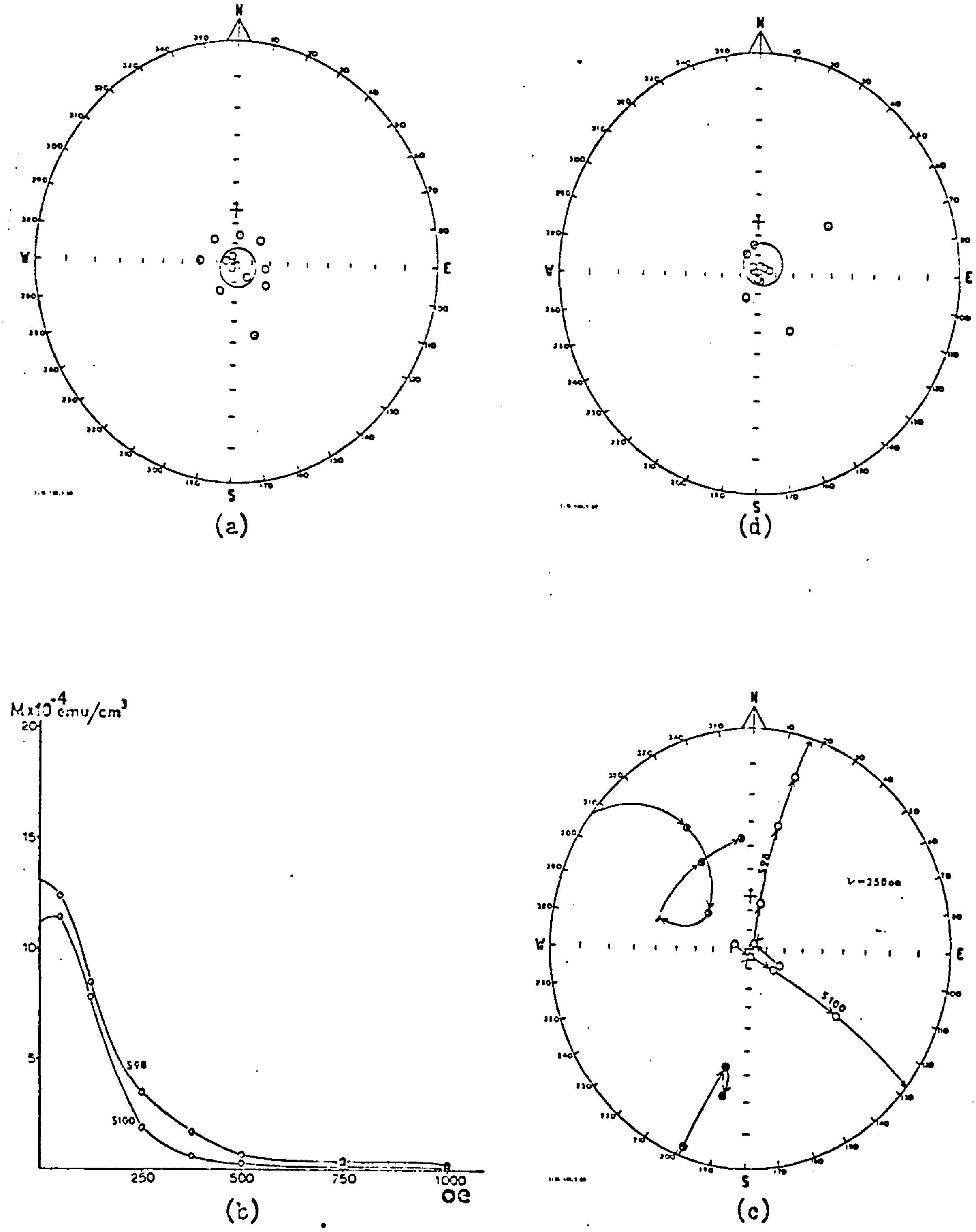
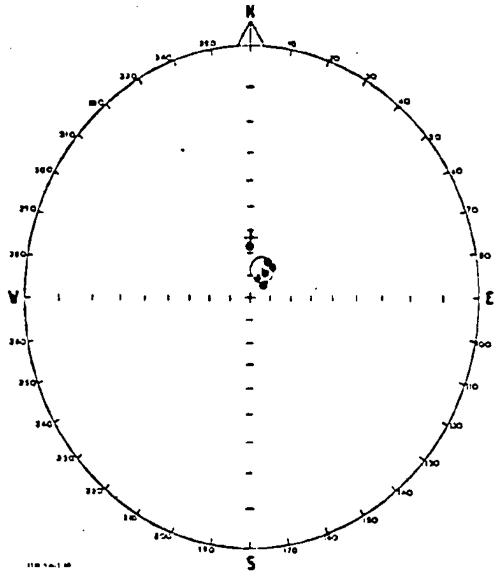
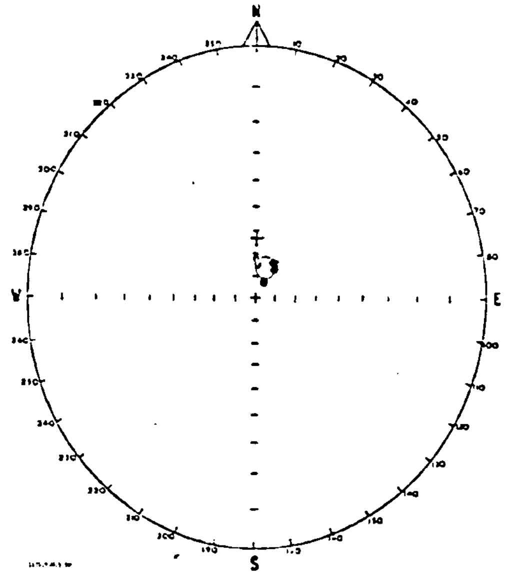


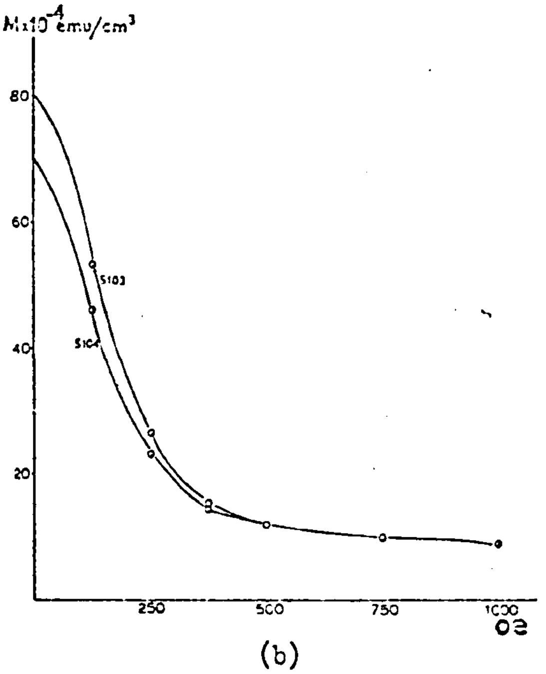
Figure 14. Direction of magnetization and effect of alternating field demagnetization in andesite specimens from Site 5, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vectors during treatment in alternating fields. (d) Directions of magnetization of Site 5 andesites after treatment in alternating fields of 250 oe (peak). The (+) indicates the direction of the present axial dipole field.



(a)



(c)



(b)

Figure 15. Directions of magnetization and effect of demagnetization in hornblende dacites from Site 6, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Directions of magnetization of Site 6 Dacites after treatment in peak alternating fields of 500 oe. The (+) indicates the direction of the present axial dipole field.

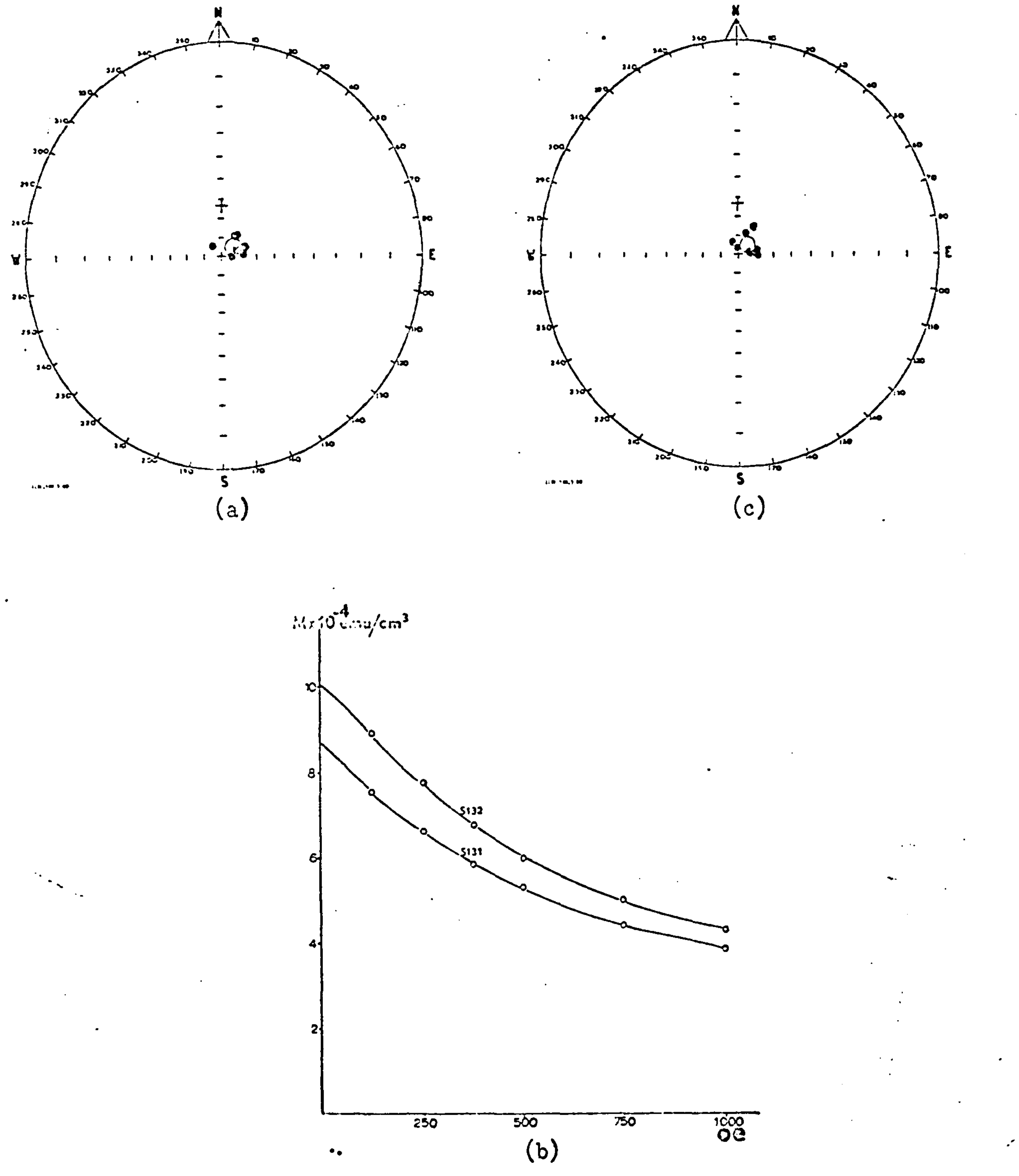


Figure 16. Directions of magnetization and effect of demagnetization in hornblende dacites from Site 8, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Directions of magnetization of Site 6 dacites after treatment in peak alternating fields of 500 oe. The (+) indicates the direction of the present axial dipole field.

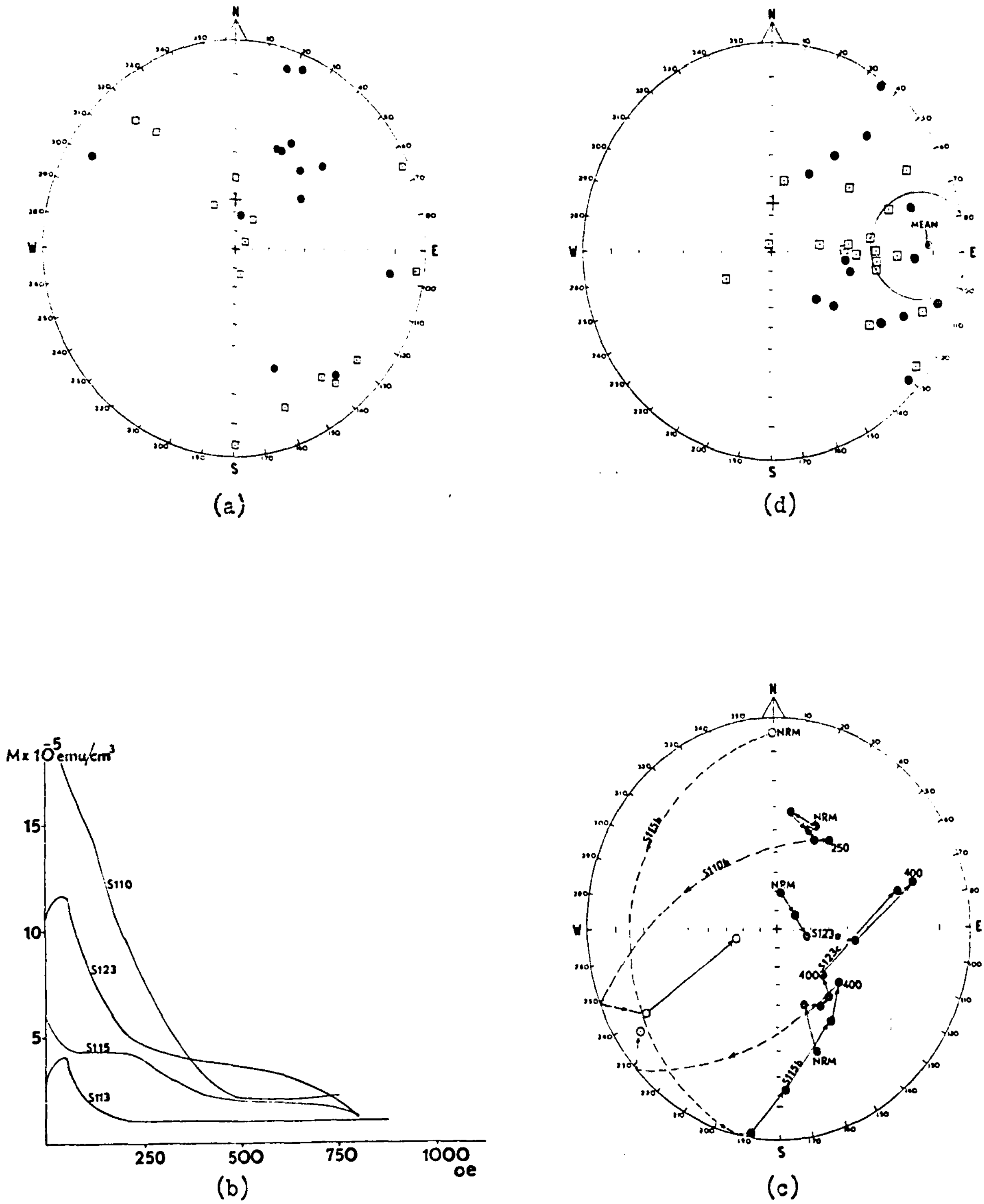


Figure 17. Directions of magnetization and effect of alternating field demagnetization in specimens from Site 7, Shemya Island. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vector directions during treatment in alternating fields. (d) Directions of magnetization after cleaning in alternating fields. Directions in (a) and (d) plotted on upper (open symbols) and lower (solid dots) hemispheres. The (+) indicates the direction of the present axial dipole field.

Table 3

Mean directions of NRM, pole positions, and associated statistics for Mid-Late Miocene sites from Shemya Island

Site No.	Lat. °N	Long. °E	N	R	D_m (°ETN)	I_m (°down)	k	α 95	P_{lat} °N	P_{long} °E	δ p	δ m	Polarity
Mid-Late Miocene Rocks:													
1	52.74	174.10	5	4.981	1.10	75.03	213.9	5.2	80.8	177.3	9	10	N
2	52.74	174.11	10	9.818	177.58	-78.91	49.6	6.9	74.1	170.8	13	13	R
3	52.73	174.13	9	8.936	311.64	76.07	125.8	4.6	63.1	126.9	8	9	N
4	52.72	174.15	6	5.981	189.49	-71.27	265.8	4.1	83.6	230.5	6	7	R
5	52.72	174.15	12	11.439	328.60	-86.03	19.6	10.1	45.8	180.0	20	20	R
6	52.72	174.11	6	5,963	24.48	76.08	133.5	5.8	73.3	213.8	10	11	N
8	52.73	174.11	8	7,948	59.72	81.34	133.8	4.8	58.2	202.6	9	9	N
Mean of Site Means (NRM)			7	6,922	6.71	80.27	76.5	6.9	71.4	180.9	13	13	M
Mean of all Cores (NRM)			56	54.397	5.13	81.80	34.3	3.3	68.7	178.0			M

N = number of specimens (sites)
R = length of vector sum of N unit vectors
D_m, I_m = estimate of the mean direction of magnetization.
K = precision parameter for D_m, I_m.
α95 = radius of circle of confidence at the 95% level for D_m, I_m.

P_{lat} = latitude of paleomagnetic pole
P_{long} = longitude of paleomagnetic pole
δp,δm = semi-axes of the elliptical error area around the pole at a probability of 95%.
Polarity (N= Normal, R=Reversed, M=Mixed)

Table 4
Mean directions of magnetization, pole positions, and associated statistics for Mid-Late Miocene sites from Shemya Island after treatment in alternating fields

Site No.	Lat. °N	Long °E	N	R	D_m (°ETN)	I_m (°down)	k	α95	P_{lat} °N	P_{long} °E	δp	δm	Polarity	AF (oe)
Mid-Late Miocene Rocks:														
1	52.74	174.10	5	4.983	4.56	77.19	229.9	5.1	77.0	182.5	9	9	N	375
2	52.74	174.11	10	8.835	195.61	-78.12	48.5	7.5	73.7	195.9	14	14	R	500
3	52.73	174.13	9	9.909	327.67	77.42	99.1	4.9	69.2	136.1	7	8	N	500
4	52.72	174.15	6	5.958	191.88	-70.05	119.9	6.1	82.8	248.8	9	10	R	500
5	52.72	174.15	12	11.136	207.04	-84.11	12.7	12.7	62.6	185.6	25	25	R	250
6	52.72	174.11	6	4.981	21.26	75.81	205.9	5.3	74.8	212.6	9	10	N	500
8	52.73	174.11	8	7.951	56.00	83.03	143.5	4.6	58.6	198.3	9	9	N	500
Mean of Miocene Site Means (AF)			7	6.959	11.27	78.79	146.8	5.0	73.4	188.7	9	9	M	250-500
Mean of all Miocene Cores (AF)			56	54.617	13.11	80.56	39.8	3.1	70.2	186.3	6	6	M	250-500
Eocene(?) Rocks:														
7	52.72	174.09	32	21.366	87.93	-11.58	2.9	18.3	-3.4	269.3	10	19	M	375

N = number of specimens (sites)
R = length of vector sum of N unit vectors
D_m, I_m = estimate of the mean direction of magnetization
k = precision parameter for D_m, I_m.
α95 = radius of circle of confidence at the 95% level for D_m, I_m.

P_{lat} = latitude of paleomagnetic pole.
P_{long} = longitude of paleomagnetic pole.
δp, δm = semi-axes of the elliptical error area round the pole at a probability of 95%
Polarity (N=Normal, R=Reversed, M=Mixed).
AF = alternating field in oersteds.

Paleomagnetic Observations II

Susceptibilities, Intensities of NRM, and Curie Points.

Variations in the rock magnetic properties of an igneous body can often provide valuable insight into its origin, subsequent history and magnetic stability (Irving, 1964). Such variations were used to establish the thermal nature of the contact at site 1, Shemya (see Appendix I of this report).

The Koenigsberger, or Q_n-ratio, defined as the ratio of the intensity of the NRM (M_{nrm}) to the bulk susceptibility (K), is often used as a general indicator of the magnetic stability of the rock. It has been shown empirically that values for this ratio of 1.0 or more are generally associated with stable remanences, whereas values less than 0.1 usually signal the presence of substantial unstable components (Irving, 1964). The build-up of unstable components and/or the decay of the primary remanence is related in many cases to viscous effects. Since, in general, these effects are time-dependant, the Q_n-ratio can sometimes be used in local situations as a guide to the relative ages of the rocks being investigated.

Viscous effects are thought to be the result of thermal agitations which tend to drive an assembly of domains to their lowest energy state. These effects take place at any temperature above 0°K, and become more important the higher the temperature. Low-coercivity components (short relaxation times) are affected by viscous magnetization/demagnetisation more than hard components (long relaxation times). Viscous demagnetization of an assembly of domains is usually accompanied by the aquisition of a secondary component parallel to the direction of the ambient geomagnetic field (VRM). In this case the total remanence is the vector sum of the remaining primary magnetization and the secondary component. Hence, the total remanence of a given rock can be expressed as:

$M_{nrm} = (M_{primary}$ - Component due to viscous demagnetization) + VRM in direction of ambient field.

Viscous decay of NRM and the deposition of VRM take place without changes in the mineralogy of the magnetic minerals of a rock. However, the rate of viscous decay is dependent on the mineralogy of the magnetic minerals. For the common rock-forming magnetic minerals the decay over geologic time is not important and the VRM is removed by alternating field demagnetization. The magnitude of viscous effects in any given rock can be estimated by observing the behavior of the rock in a high steady field; allowing the viscosity coefficient to be measured, and extrapolated to the earth's field.

Physiochemical changes in the ferromagnetic mineral fraction of a rock can change both the remanence and the bulk susceptibility. Changes which have taken place in the latter case cannot be detected by paleomagnetic methods since the initial susceptibility cannot be determined. However, it is often possible to detect changes which have affected the mineralogy of a rock by petrographic methods.

Mean site susceptibilities, intensities of NRM, and Q_n-ratios are summarized in Table 5 and displayed in Fig. 18. The variations observed in Fig. 18 conform to the general pattern established during the demagnetization of the specimens. Those sites whose specimens have relatively large hard components of magnetization, and yield directions which do not disperse appréciably after treatment in alter-

Table 5. Mean Site Susceptibilities, Intensities of NRM, and Q_n-Ratios, Shemya Island

Site No.	N	K (emu/cm^3)	M_{nrm} (emu/cm^3)	Q_n	Rock Type
1	5	3.17×10^{-3} (0.14)	2.50×10^{-3} (0.48)	0.79	Hornblende Andesite
2	10	2.02×10^{-3} (0.18)	3.61×10^{-3} (0.78)	1.78	Hornblende Dacite
3	9	1.71×10^{-3} (0.30)	3.36×10^{-3} (0.41)	1.95	Tholeiitic Basalt
4	6	3.47×10^{-3} (0.15)	4.16×10^{3} (2.62)	1.15	Andesitic Basalt
5	12	3.13×10^{-3} (0.30)	1.46×10^{-3} (0.38)	0.47	Hornblende Andesite
6	6	1.92×10^{-3} (0.13)	6.79×10^{-3} (0.70)	3.53	Hornblende Dacite
7	13	1.36×10^{-3} (0.28)	0.05×10^{-3} (0.02)	0.04	Palagonitic Tuff Breccia
7	2	3.82×10^{-3} (NA)	0.56×10^{-3} (NA)	0.15	Graywacke
8	8	0.55×10^{-3} (0.14)	0.69×10^{-3} (0.13)	1.26	Hornblende Dacite

K = Mean low-field bulk susceptibility; arithmetic mean standard deviation in parentheses.

M_{nrm} = Mean intensity of NRM; arithmetic mean standard deviation in parentheses.

$Q_n = M_{nrm}/K$.

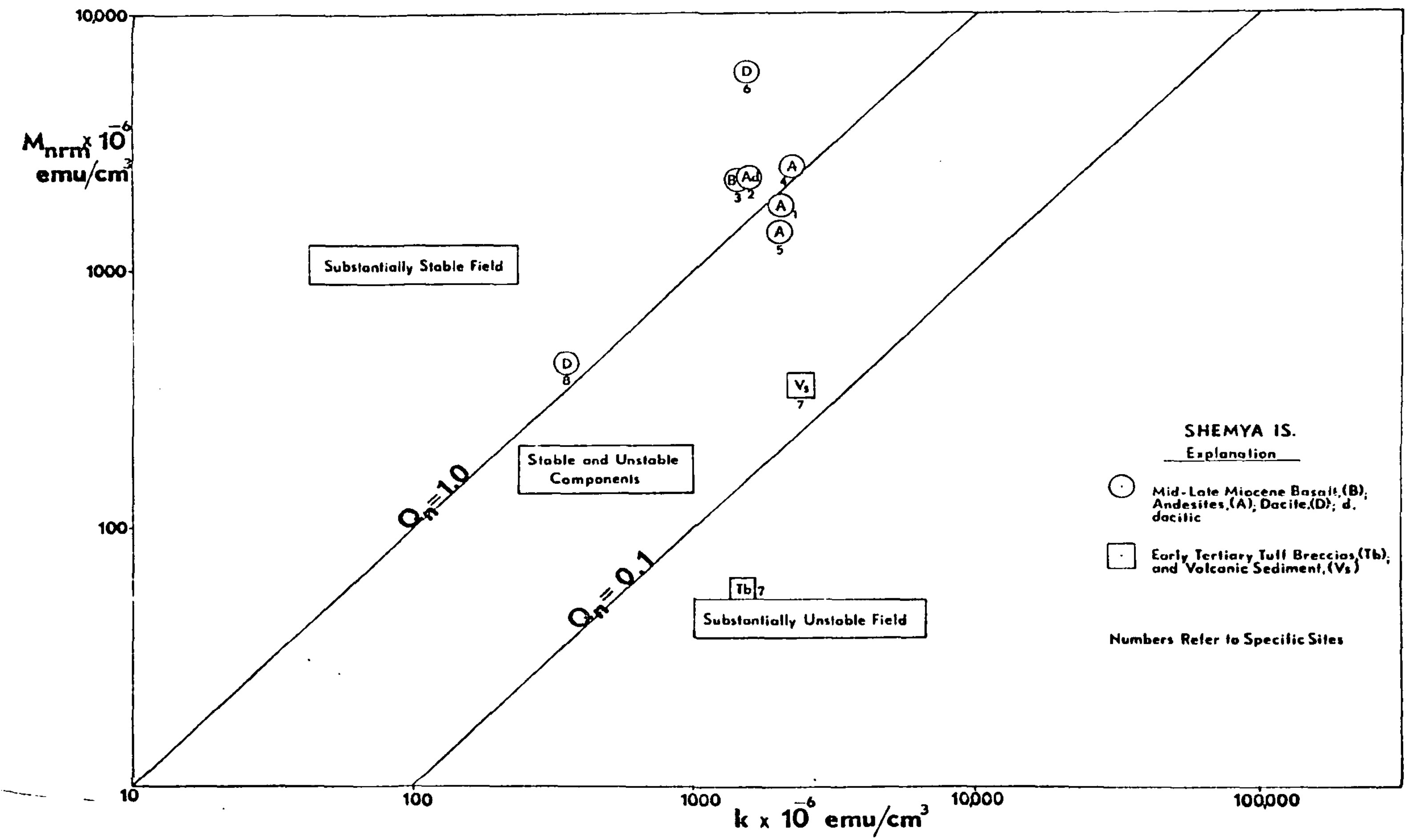


Figure 18. Relation between Intensity of NRM and bulk magnetic susceptibility in Tertiary rocks from Shemya Island.

nating fields, also have relatively high Q_n-ratios and fall in the substantially stable category. Directions of specimens from sites 1 and 5 dispersed after treatment in high alternating fields. These specimens have smaller hard components and, correspondingly, lower Q_n-ratios. They are considered stable but only marginally so.

The Q_n-ratio for site 7 (Cretaceous-Eocene) is quite low and indicates the presence of substantial unstable components. The demagnetization data indicate that much of the primary magnetization has been destroyed, leaving behind weak components which are easily demagnetized. At least some of the soft components are secondary. The bulk susceptibilities are usual for rocks of these types, and a basic petrographic examination of the rocks disclosed the presence of relatively abundant opaque oxides. While it is not suggested that primary components are non-existant in these rocks it would appear that such components have suffered considerable viscous decay and are probably too weak to measure accurately.

Curie Point Data

Curie point temperature curves for selected samples from each of the Mid-Late Miocene sites are illustrated in Figs. 19-22. In all cases major magnetic transitions occurred at temperatures below the Curie point of pure magnetite (578° C). Laboratory heating caused significant chemical and/or textural changes in specimens from sites 2, 6, and 8. These changes are indicated by the departure of the cooling curves from the curves generated by rising temperatures. Curves showing this characteristic have been termed "irreversible ordinary types" by Nagata and Akimoto (1950). Only minor departures

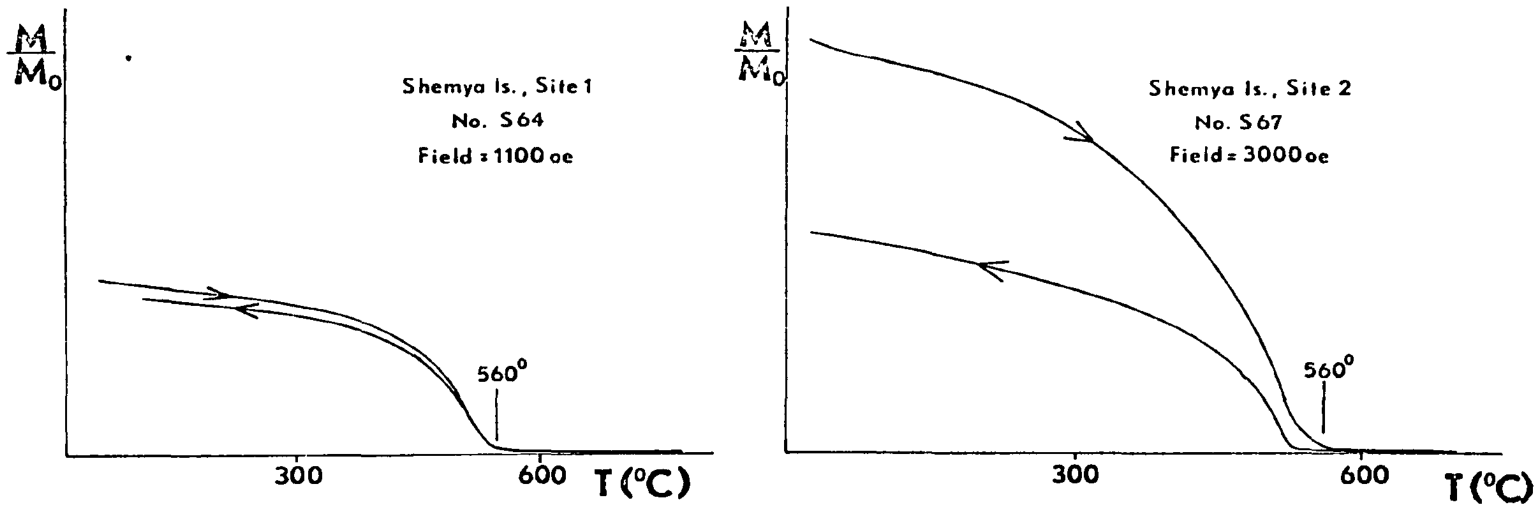


Figure 19. Curie temperature curves of selected specimens of andesite from sites 1 and 2, Shemya Island.

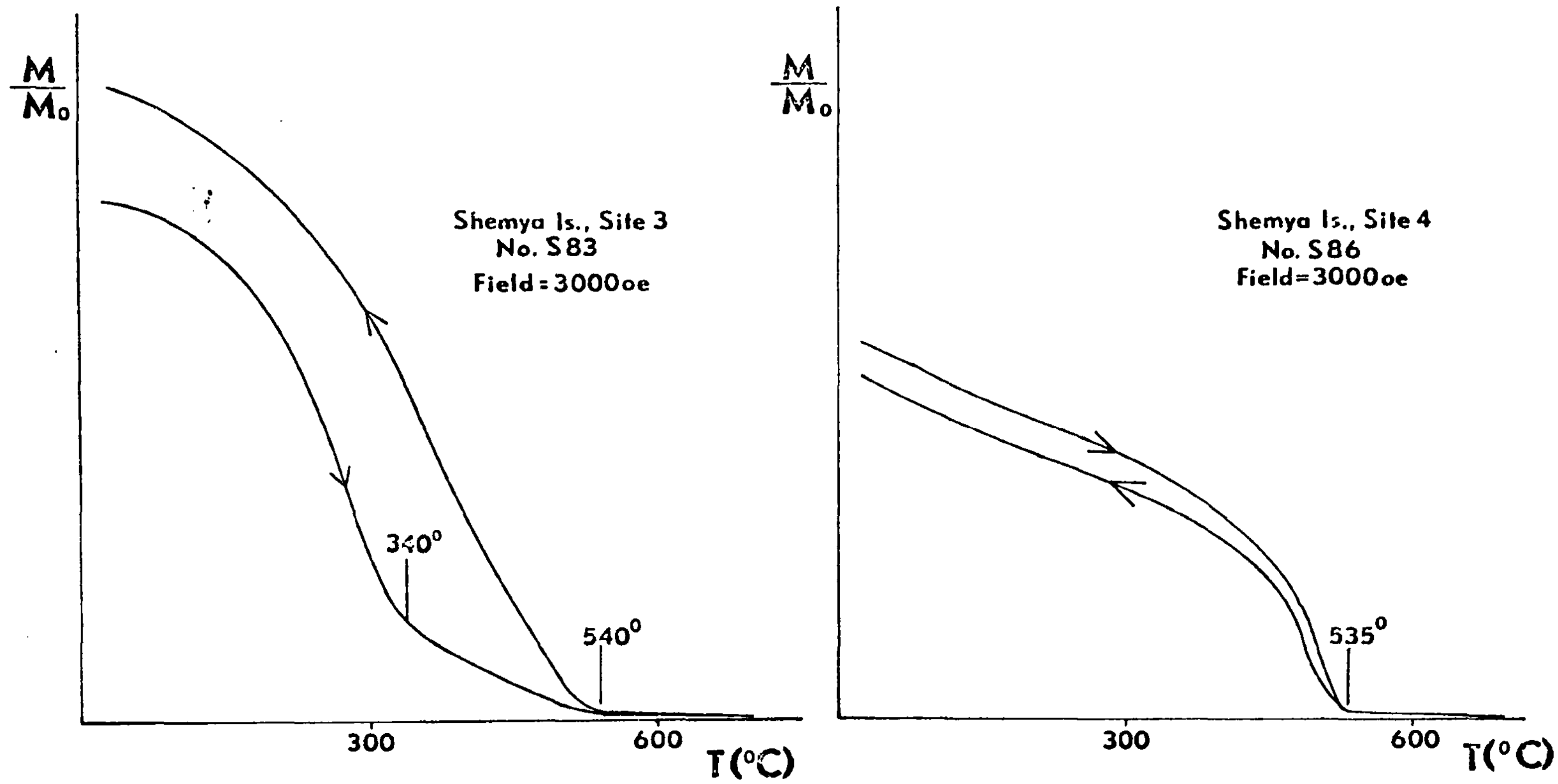


Figure 20. Curie temperature curves of selected specimens of basalts and andesites from sites 3 and 4, Shemya Island.

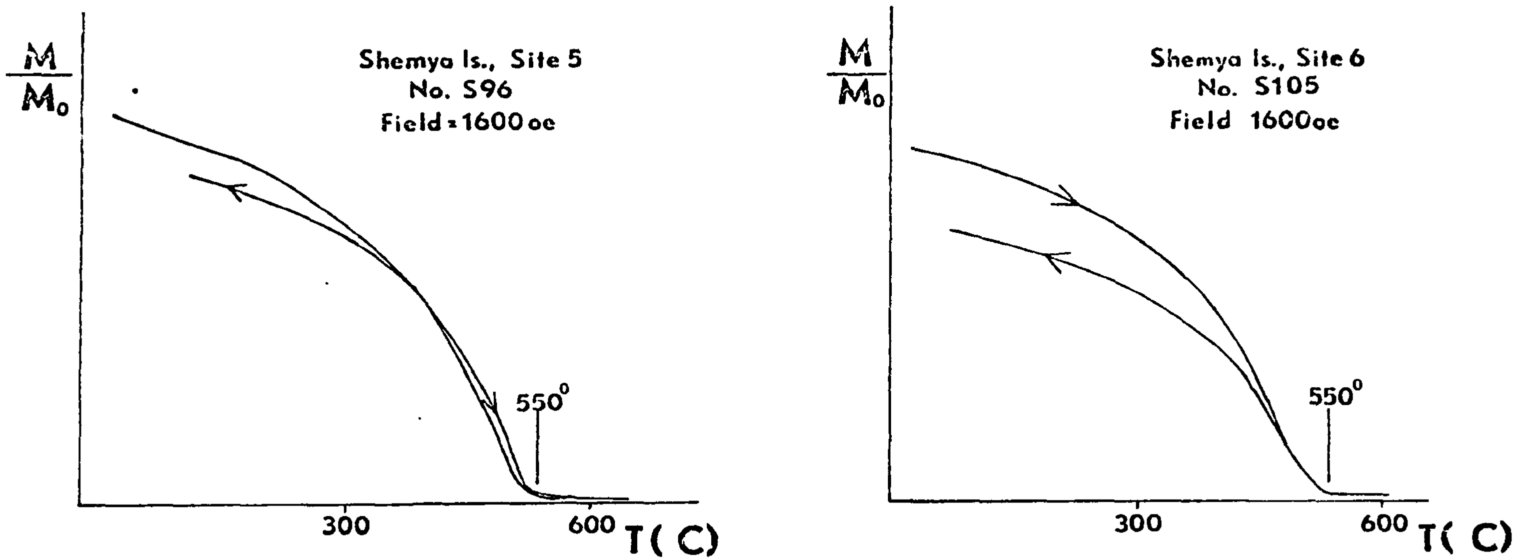


Figure 21. Curie temperature curves of selected andesite and basalt specimens from sites 5 and 6, Shemya Island.

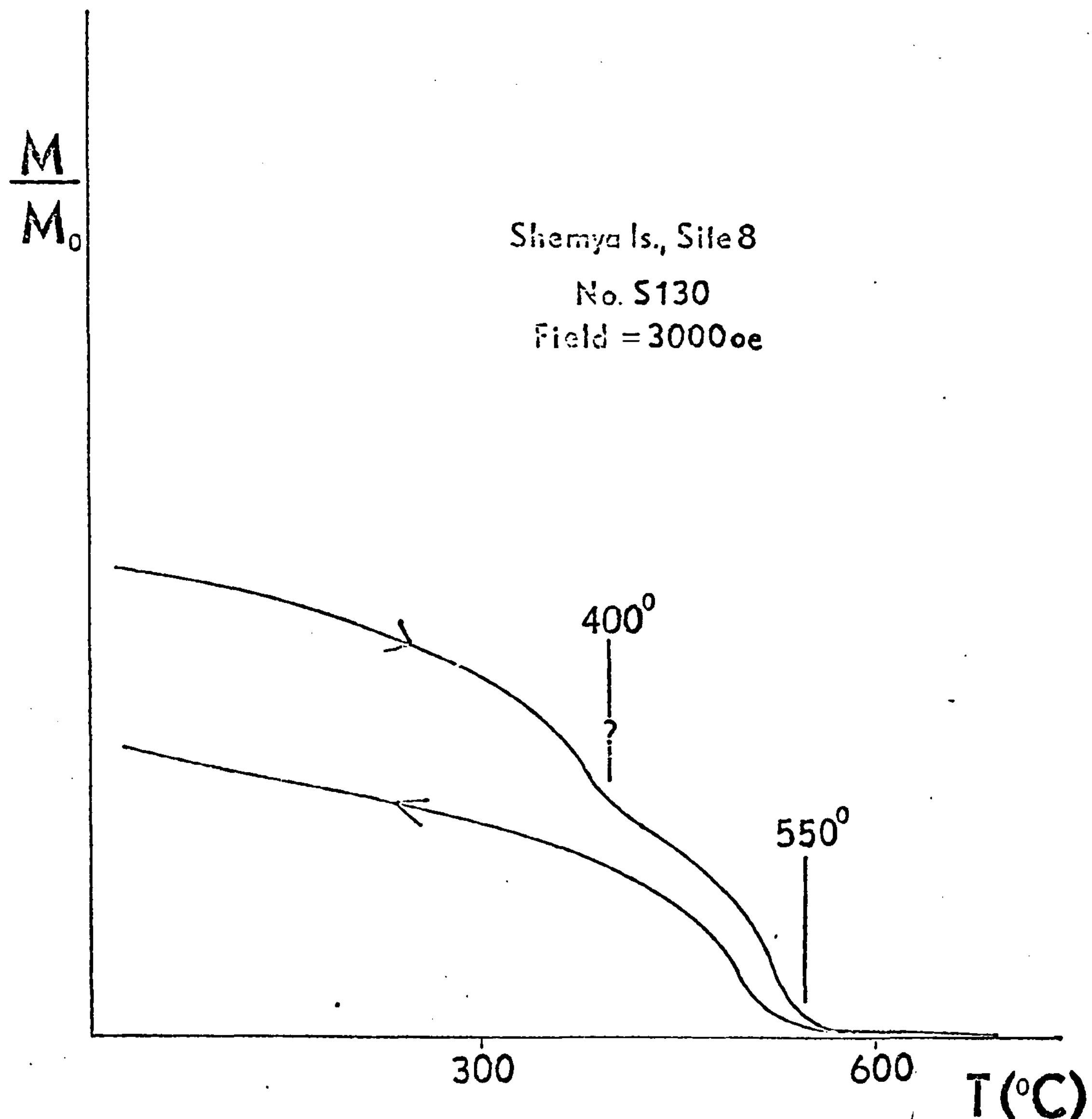


Figure 22. Curie temperature curve for selected specimen of dacite from site 8, Shemya Island.

in the forms of the heating and cooling curves were observed for specimens from sites 1, 4 and 5. These curves provide an example of the "reversible ordinary type".

The heating curve for the specimen from site 3 behaved in a stepwise fashion, magnetic transition points occurring at 340°C and 520°C. The cooling curve for the specimen was smooth but showed substantial departure from the heating curve. Curves of this type are termed "Irreversible extraordinary types". The specimen from site 8 also underwent two magnetic transitions during the heating process. A relatively minor transition occurred at approximately 400°C. Following the method of Nagata and Akimoto (1950), the major transition at 540°C was chosen as the main Curie temperature of the rock.

Curie temperatures of rocks depend on the composition of the ferromagnetic constituents contained therein (Nagata, 1961). Data presented by Nagata and Akimoto (1950) indicate that rock Curie temperatures decrease as FeO increases (Fig. 23). Available chemical data from Shemya sites were combined with the Curie point data and plotted in a manner consistant with the technique used by the Japanese investigators. In a review of their data this author noted that the field defined by basalts and andesites with low Curie points was formed by rocks having "irreversible extraordinary type" curves.

It is not surprising that the trend established by the four andesites and dacites from Shemya differs significantly from that defined by the Japanese data. The Curie point of pure magnetite is 578°C. If indeed there exists a true relationship between rock Curie temperatures and the ratio $Fe_2O_3/Fe_2O_3 + FeO$, then the trend must become approximately

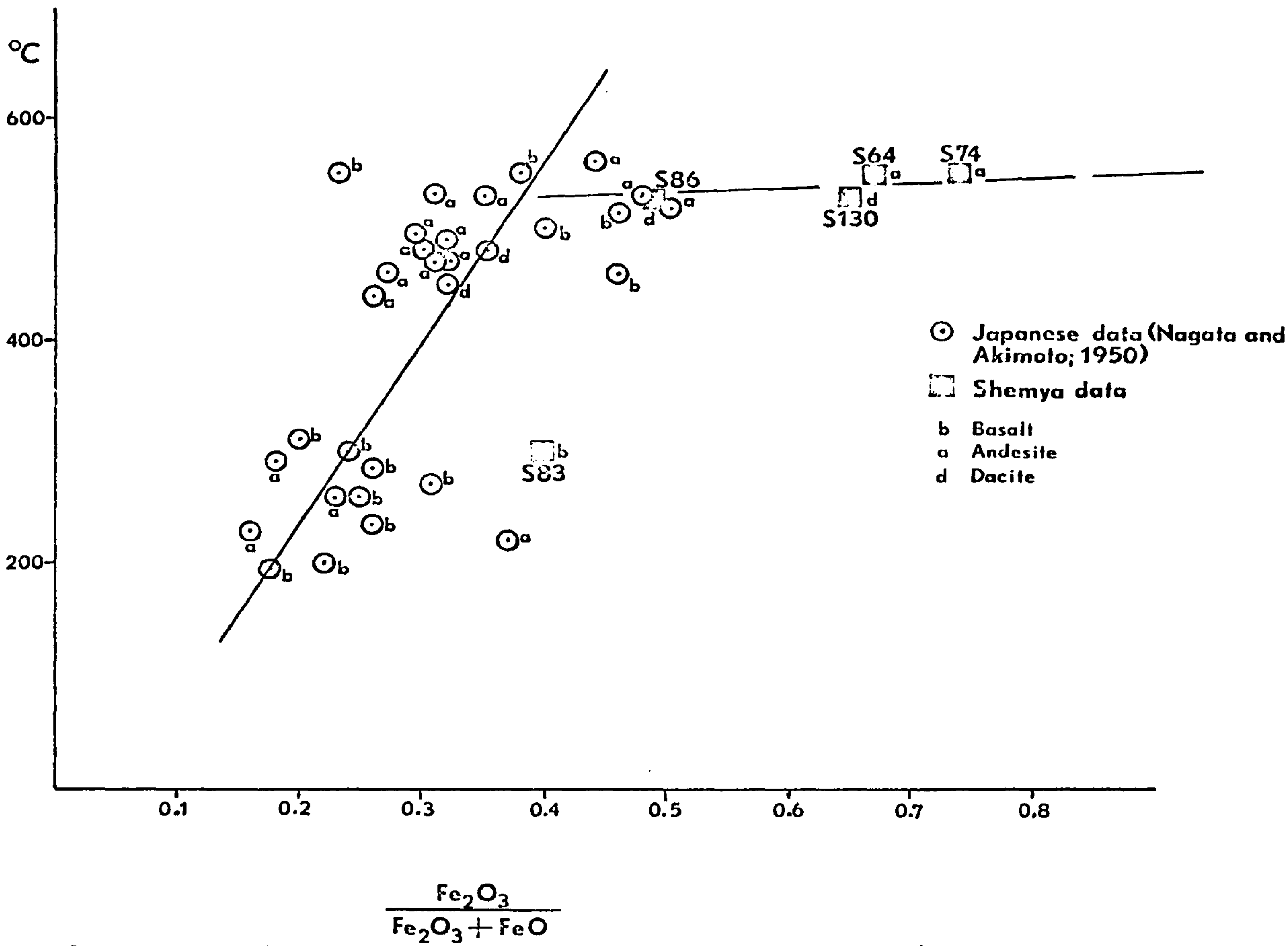


Figure 23. Dependence of Curie temperature on the ratio of $Fe_2O_3/(Fe_2O_3 + FeO)$ of basic and intermediate extrusive and hypabyssal igneous rocks from Japan and Shemya.

asymptotic to the maximum Curie temperature as values of the ratio Fe_2O_3/Fe_2O_3 + FeO increase. At present the data are too few and too scattered to predict the exact path of this portion of the curve with any certainty.

With respect to the distribution of rock types in Fig. 23, it is noted that basalts predominate in the field defined by the low-Curie temperature rocks. On the other hand, the field defined by high-Curie temperature rocks is populated chiefly by andesites and dacites. The low-Curie points probably reflect the presence of limenite-hematite series minerals in the basaltic rocks. The high-Curie temperatures reflect the presence of minerals in the ulvospinel-magnetite series in the andesitic and dacitic rocks. The gap in between the two fields, defined by an absence of Curie points between 320°C and 420°C, may be due to the immiscibility of the two series. Alternatively, the gap could also be due to differences in the molecular percentage of TiO_2 in the magnetic phases. The spinels in the andesite-dacite field may be poorer in TiO_2 and thus have a higher Curie point.

Discussion of Results

Mid-Late Miocene rocks from Shemya satisfy the following gererally accepted criteria of magnetic stability:

1. In spite of the relatively young ages of the rocks, the mean site directions are significantly divergent from the direction of the axial dipole field for Shemya.

2. Mean site directions remained relatively fixed after treatment of the rocks in high alternating fields.

3. In most cases the hard component of remanent magnetization could not be demagnetized; even in alternating fields as high as 1000oe (Fig. 24).

4. The presence of reversed sites whose directions, when normalized, do not differ significantly from those of normally polarized rocks (Fig. 25, Table 4).

5. Mean site values of the ratio M_{nrm}/K near, or greater than, 1.0.

6. The presence of a high Curie point component generally indicates a high stability (assuming the mineral involved dates from the time of origin of the rock).

Unfortunately magnetic stability could not be established for Early Tertiary (?) rocks from site 7. The experimental data indicates that the primary magnetization has decayed to an extent that it cannot be gainfully measured with the present equipment. This is regretable since comparison with directions in Eocene rocks from Adak would have been valuable from the standpoint of tectonic analysis of the arc.

Paleomagnetic directions at the various sites on Shemya are

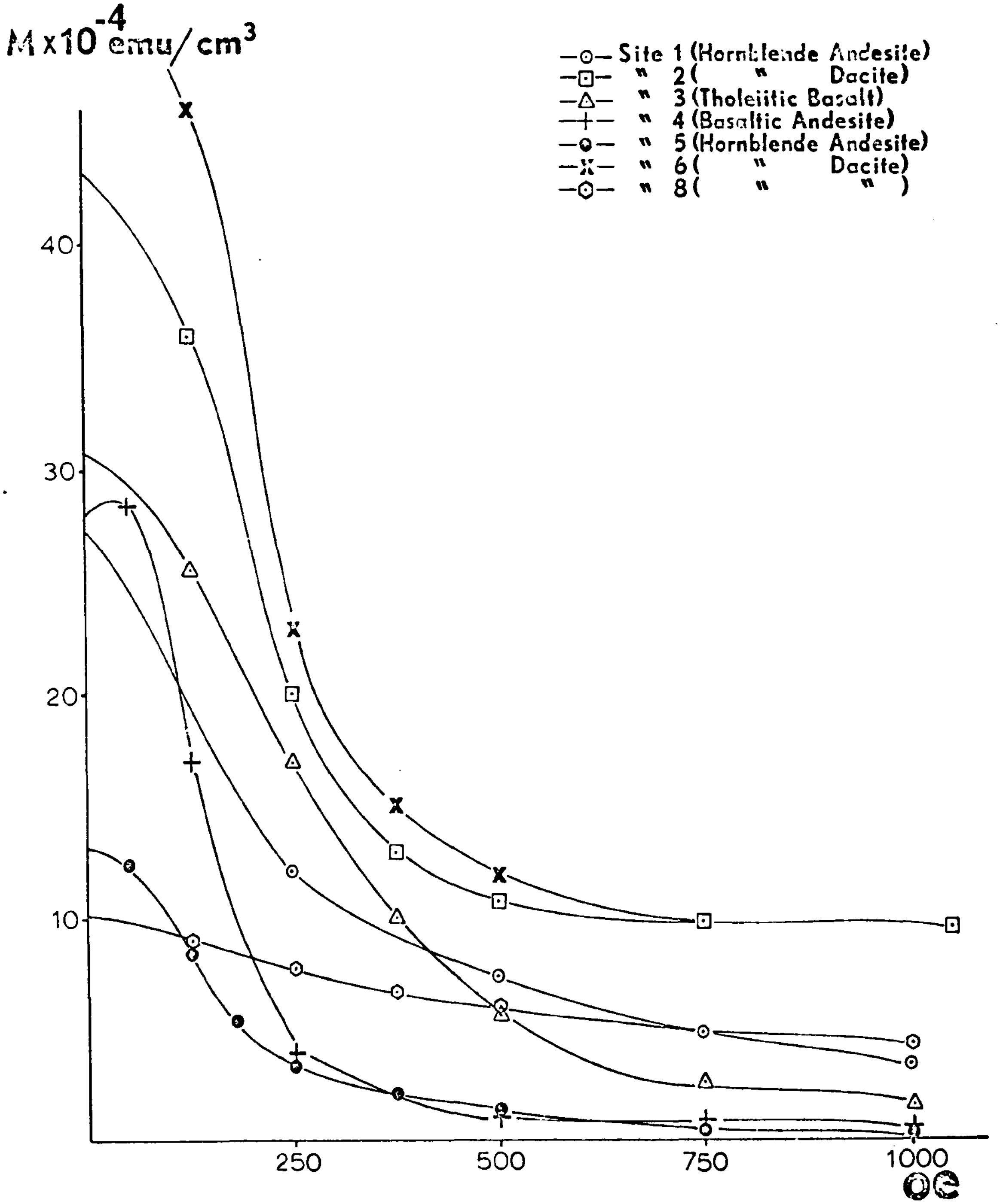


Figure 24. Compiled demagnetization curves for selected Mid-Late Miocene rocks from Shemya Island.

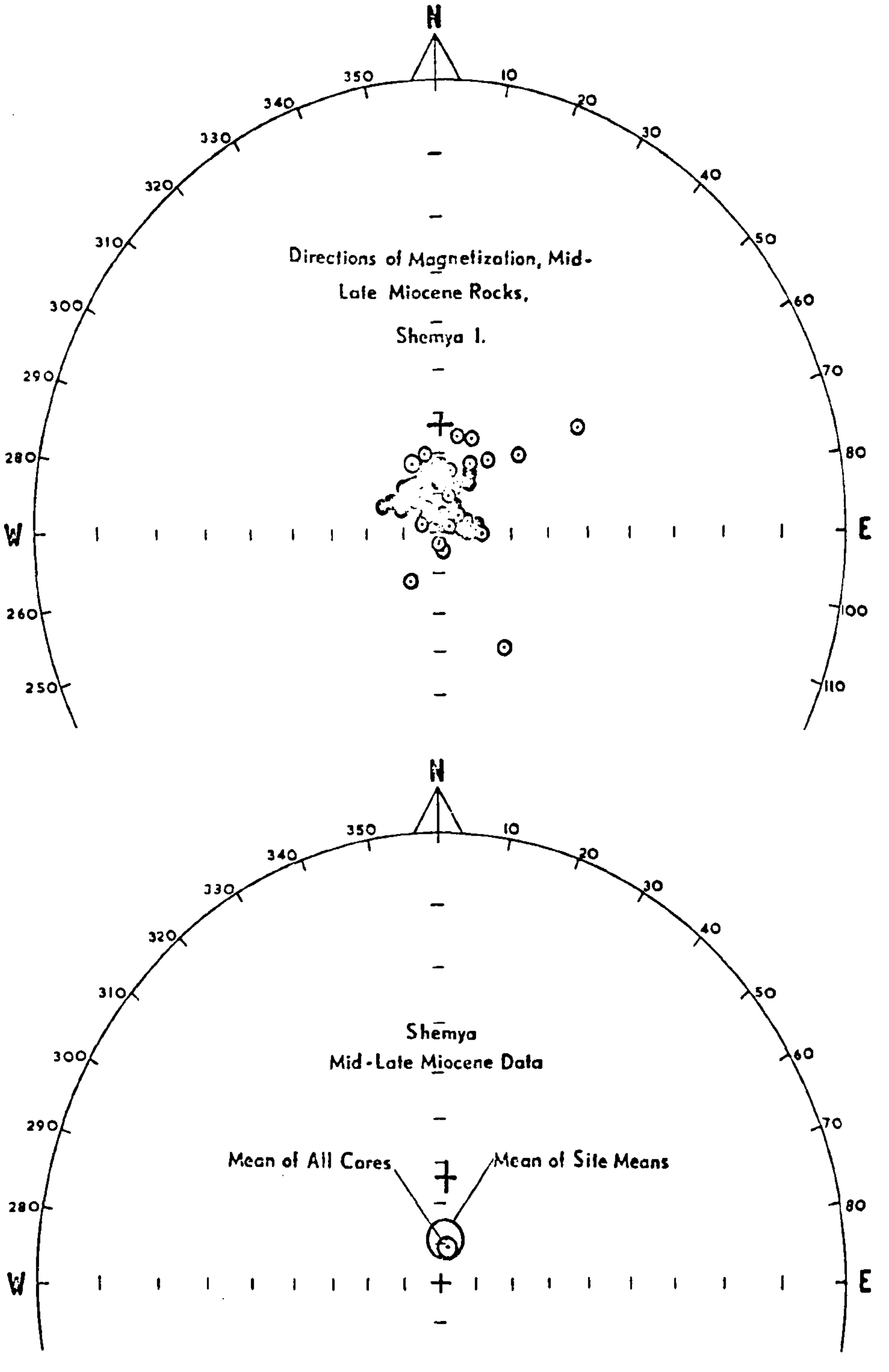


Figure 25. Directions of remanent magnetization (combined data) in Mid-Late Miocene rocks in Shemya Island.

illustrated in Fig. 26. Directions with reversed polarities are indicated by negative inclinations. Translating the paleomagnetic analysis into geologic terms, several conclusions regarding the origin of the Mid-Late Miocene rocks emerge. First, rocks at sites 2, 4 and 5 were formed either at the same time during the same reverse-polarity interval, or, during two different reverse-polarity intervals. Since sites 2 and 5 consist of intrusive rocks formed at hypabyssal depths, and since site 4 is regarded as a volcanic vent which cuts the intrusives, the interpretation that the reversed rocks were formed during two different reverse polarity intervals is preferred. Following the same line of thought, two normal-polarity intervals appear to be represented by rocks at sites 1, 3, 6, and 8. The errors in the radiometric ages from sites 3 (12.3 ± 1.5 m.y.) and 8 (15 ± 3 m.y.) overlap, hence this criterion fails to separate the sites in time. However, the glassy tholeiite vent at site 3 obviously formed at, or very near the surface, whereas the andesites and dacites at sites 1, 6 and 8 are clearly hypabyssal. A significant time span between the formation of the two is implied and two different normal-polarity intervals are probably represented.

The paleomagnetic evidence indicates that multiple intrusions, rather than a single event, formed the andesite-dacite porphyry intrusive complex. The grain size and textures of the rocks imply that they cooled relatively quickly, perhaps in times of the order of 10^3 - 10^4 years. These times should be long enough to average out the effects of secular variation on the remanence directions and the small scatter of data points about the means bears this out. The mean length of polarity intervals in the Tertiary is

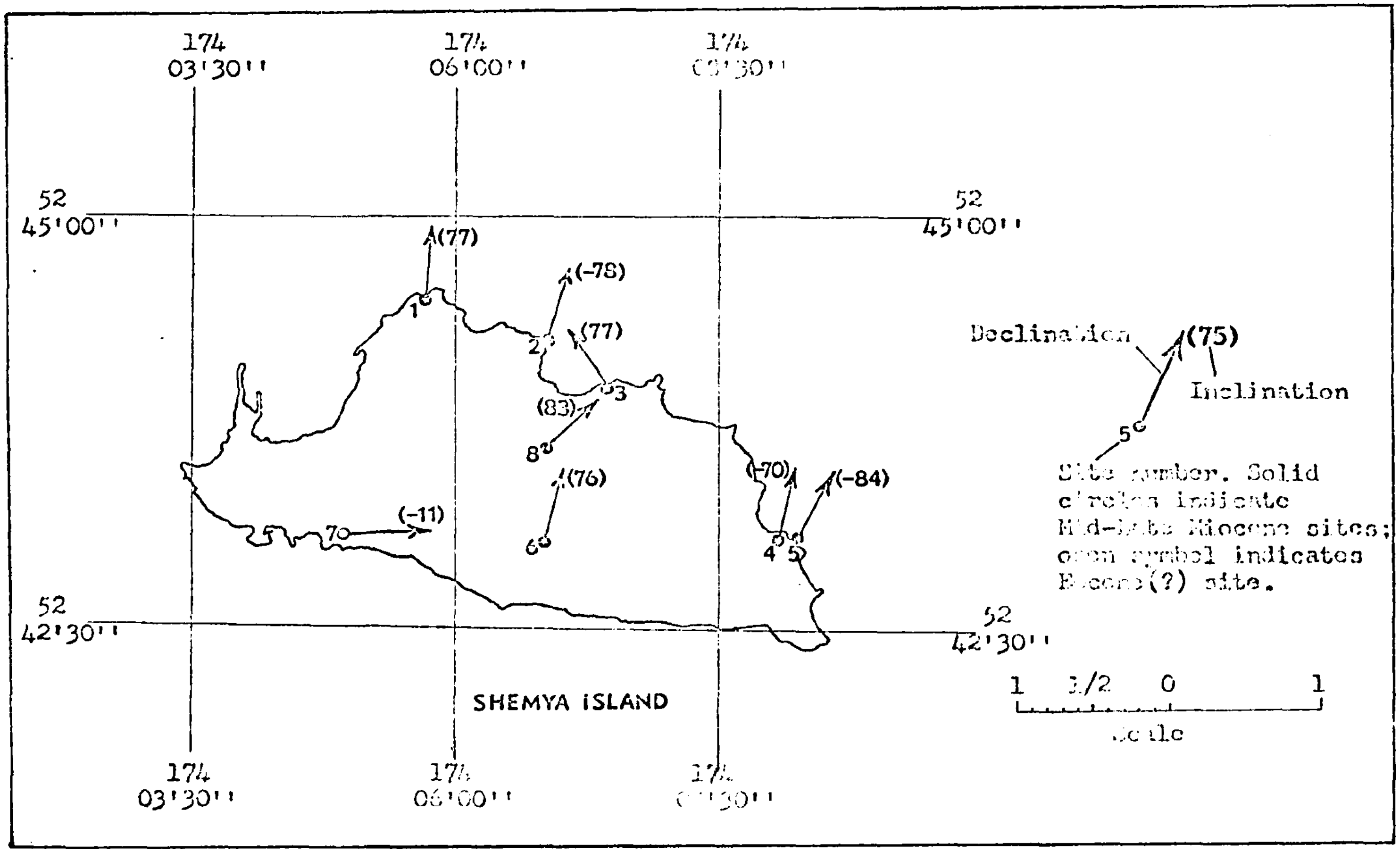


Figure 26. Paleomagnetic direction in rocks of Mid-Late Miocene and Eocene Age in Shemya Island.. Site mean declinations are given by the arrow. Mean inclinations are given in brackets next to heads of the arrows.

estimated to be 0.22 m,y. (Cox, 1968), and estimates of the amount of time necessary for the main field to reverse its polarity are in the range from a thousand to a few thousand years. If the emplacement of the porphyries took place as a single event, in time to have recorded both normal and reverse-polarity intervals; then this would be seen in a between-site dispersion of mean vector directions. Such a dispersion is not observed. It is therefore concluded that the Shemya intrusive complex was emplaced as multiple intrusions (at least two) during Mid-Late Miocene times. It is probable that the complex was emplaced over a very short period of geologic time, perhaps something in the order of 0.5×10^5 to 10^6 years, with 10^5 years as a best guess. The basaltic vents at sites 3 and 4 probably represent distinct normal and reverse-polarity intervals, since the vents were formed after the porphyries had been uplifted (either regionally or by displacements along local faults) to a position at or very near sea level. Hence, four distinct polarity intervals are thought to be represented in Mid-Late Miocene rocks in Shemya

The mean site direction (reversed sites normalized) and pole position for the Mid-Late Miocene sites are shown in Figure 27. The pole position is displaced to the south of Miocene positions derived from other North American sites. The paleolatitude derived is considerably north of the present latitude of the island. The implications of these results are discussed in the concluding chapter of this report.

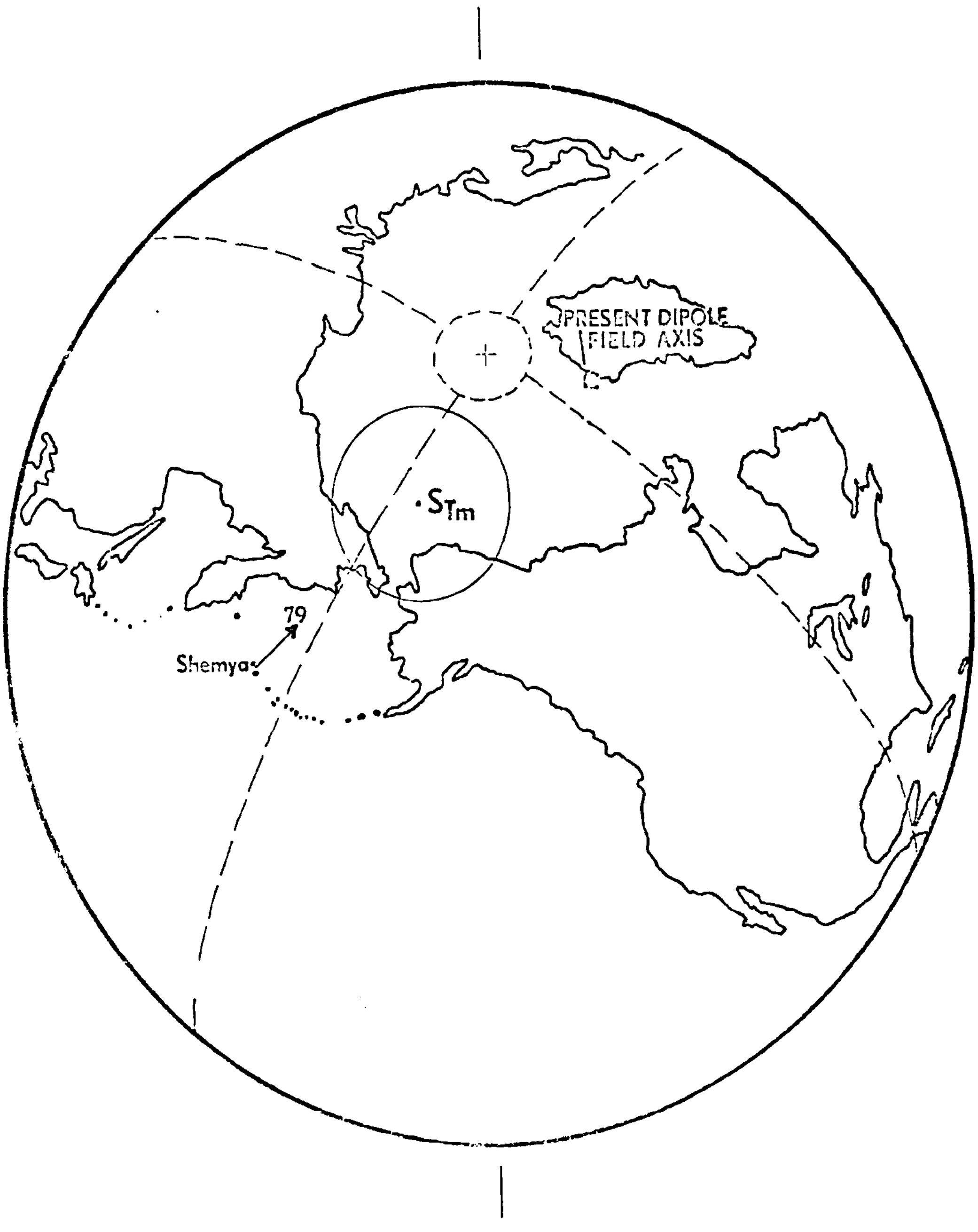


Figure 27. Site mean paleomagnetic direction and pole position determined from Mid-Late Miocene basalts, andesites, and dacites from Shemya Island.

CHAPTER IV

PALEOMAGNETISM OF NORTHERN ADAK ISLAND

Geologic fieldwork and paleomagnetic sampling were carried out on Adak Island during the summers of 1967 and 1968. In all, 200 core specimens were collected from 14 sites on the northern end of the island. A total of 131 cores from 4 geologically distinct units were collected by the author and Dr. D. B. Stone, Geophysical Institute, University of Alaska, during July and August of 1967. Additional specimens from 3 of these units were collected during the summer of 1968 by Dr. Stone and Messrs. D. K. Bingham and B. N. Chatterjee. As was the case on Shemya Island, a dense cover of vegetation restricted sampling to sea cliff areas, quarries and road cuts.

The specific locations of paleomagnetic sampling sites are shown in Figure 28. The geology shown was compiled by R. R. Coats, U. S. Geological Survey, who mapped the island in the summer of 1946. The results of his reconnaissance are contained in the U. S. Geological Survey Bulletin 1028-C, Geology of Northern Adak Island, Alaska, (1956b).

The southern and central portions of the area mapped consist of faulted, folded and highly altered volcanic rocks of Eocene age, designated by Coats as the Finger Bay Volcanics. The Finger Bay Volcanics are intruded by Mid-Late Tertiary (?) gabbro and five domical masses of hornblende andesite porphyry. The mountainous northern portion of Adak Island consists of basic and intermediate lava flows, volcanic domes, and volcanic ejecta and sediments associated with three eruptive centers: Mount Moffett Volcano, Mount Adagdak Volcano and Andrew Bay Volcano.

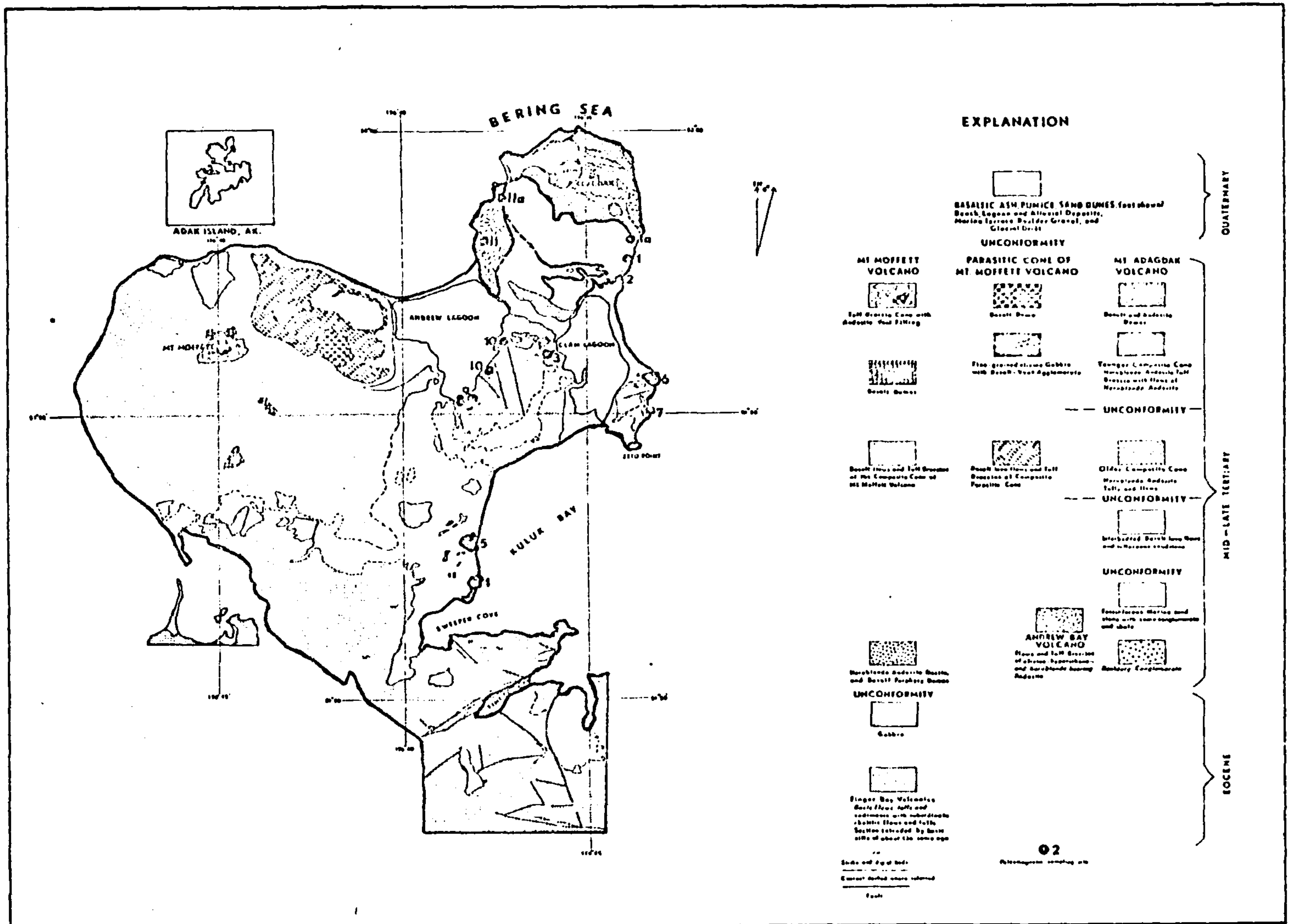


Figure 28. GEOLOGIC MAP OF NORTHERN ADAK ISLAND, ALASKA

Mount Moffett and Mount Adagdak Volcanos are Quarternary in age and according to Coats, at least in part contemporaneous. A potassium-argon determination on a specimen from the basal portions of the Adagdak pile (sites 1, 1a, and 2) was performed by Mobile Oil Corporation's Field Research Laboratory. The specimen, a fresh olivine basalt analysed as a whole rock sample, gave dates of 0.0 $\pm$ 0.16 million years and 0.0 $\pm$ 0.23 million years. In the opinion of the analyst, it is highly unlikely that the specimen dated could be any older than 0.5 million years.

The basal Adagdak volcanics lie unconformably on the hornblende andesite flows of Andrew Bay Volcano (sites 11 and 11a). Coats estimates that these rocks are no older than Late Tertiary or Quarternary. Paleomagnetic results of the present study tend to support his view in that the mean direction obtained for the Andrew volcanics does not differ significantly in direction from that obtained for the basal Adagdak volcanics (Fig. 31).

The ages of the hornblende andesite porphyry domes (sites 4, 5, 6 and 7) are not known with any certainty though an unconfirmed K-Ar age determination indicates an age of about 3 m.y. They show none of the intense alteration and deformation associated with the Finger Bay Volcanics which they intrude. They are therefore clearly younger than Eocene and, in the opinion of this author, younger than the major deformation which uplifted the Aleutian Ridge. On the other hand, they have been glaciated and their present form is erosional rather than constructional. Furthermore, they differ petrographically from the Quaternary igneous rocks and show no obvious geographic relationship to the three principal volcanic centers (Coats, 1956b). They are therefore considered to be Mid-Late Teriary in age.

On the basis of plant fossils found in coarse sandstones just south of the abandoned runway of Mitchell Field (immediately adjacent to and southeast of site 10), Coats assigned a tentative Late Paleozoic age to the Finger Bay Volcanics. The fossils consist of some leaf impressions identified by R. W. Brown, U. S. Geological Survey, as Annularia stellata (Schlotheim) Wood, a primative horsetail of Pennsylvanian or Permian age. Southern Adak and adjacent Kagalaska Island were studied by Fraser and Snyder (1959). They could not determine the relationship between the isolated fossiliferous outcrops on northern Adak and the Finger Bay Volcanics elsewhere on the island and on Kagalaska. However, because of the petrographic similarities with sequences of the early marine series on Kanaga Island 10 miles to the west, they assigned a Tertiary age to the Finger Bay Volcanics on Southern Adak and Kagalaska Island. The issue was finally resolved by D. W. Scholl and others (1969) of the U. S. Geological Survey. They found macrofauna of probable Eocene age, and foraminiferal fauna of definite Eocene age in bedded sediments just above the Annularia - bearing beds. The rock matrix of Annularia - bearing sediments was examined and a substantial dinoflagellate flora of Early Tertiary age was discovered. It was agreed by concerned parties in the U. S. Geological Survey that the Annularia fossils were in fact not diagnostic of the age of the section, (D. W. Scholl, personal communication to D. B. Stone, 1969).

Further complications were introduced when an attempt was made by the present investigators to confirm the age of the Finger Bay Volcanics in the northern area by using completely independent techniques. A specimen of andesite from site 10 was dated radiometrically by Dr. Paul Gast, Lamont-Doherty Geological Observatory of Columbia University. The specimen was collected in a tabular andesite body associated with a sequence of stratified sandstones, siltstones and shales inter bedded with basaltic flows and/or penecontemporaneous sills. The section dips to the northwest at about 45°. The upper and lower contacts of the andesite body are concordant and the body was originally interpreted, on petrographic grounds, as a flow unit. However, the specimen, analysed as a whole rock sample, gave a date of 5.1 million years. In his report Dr. Gast states:

> "....By comparison with other rocks we suspect that as much as 50% argon leakage may have occurred in this rock. Thus it may possibly be as old as 10 million years. I do not see any possibility that it could be 30 or 40 m.y. old....."

The paleontologic evidence which points to an Eocene age for the section is virtually indisputable, therefore, if correct, the relatively young age obtained for the andesite specimen implies that the unit occurs as a sill rather than a flow. If it is assumed that the emplacement of the sill occurred prior to the deformation of the section then this might imply that the uplift and deformation of the early marine series in the area of Adak Island took place much later in the Tertiary than in the Rat and Near Islands Groups. On the other hand the emplacement of the sill may have taken place as a post-deformation igneous event, though this would seem unlikely on paleomagnetic evidence.

Because of the uncertainty in age dates for this section, specimens from site 10 are included with the rest of the Finger Bay Volcanics for the purpose of the paleomagnetic analyses.

Description and Petrography of Sampling Sites

The petrography and chemistry of most of the Tertiary and Quaternary igneous rock units comprising Northern Adak are discussed in some detail by Coats (1952, 1956b). Descriptions of localities and specimens collectected in this investigation are summarized in Table 6. A brief description of the petrography of the specimens follows.

Adagdak Volcanics

Alkali Olvine Basalt: Phenocrysts of forsteritic olvine, augite, plagioclase (An55) and magnetite are set in a fine-grained intergranular to sub-oophitic matrix, consisting of blocky plagioclase, clinopyroxene, olivine, minor quartz, alkali feldspar, epidote and rare hematite.

Hornblende-bearing Basaltic Andesite: Phenocrysts of labradorite, diosidic clinopyroxene, oxyhornblende and magnetite are set in a fine-grained felted groundmass consisting of plagioclase, devitrified volcanic glass, Fe-oxides and minor chlorite and calcite. Glomeroporphyritic aggregates og plagioclase and clinopyroxene occur frequently.

Andrew Volcanics

Olivine-bearing Hornblende-Hypersthene Andesite: Phenocrysts of zoned and unzoned plagioclase (An45), oxyhornblende, clinopyroxene, hypersthene, olivine and magnetite are set in a felted matrix consisting of plagioclase (An34), minor alkali feldspar, secondary biotite after amphibole, devitrified glass in varying amounts, chlorite, epidote, minor carbonate, Fe-oxides and secondary quartz. Iddingsite occurs commonly

Table 6. Description of Sampling Localities and Specimens

Site Nos.*	Description of Sites	Specimen Nos.
	<u>Adgdak Volcanics</u>	
1	Horizontal flows of olivine basalt which conformably overlie 25 meters of fine-grained tuffaceous sandstones exposed in sea cliffs on the east side of Mount Adagdak.	S140-S149
1a	Similar to above.	S360-S377
2	Flow or conformable sill of hornblende-bearing basaltic andesite; somewhat lower in the section than the above flows.	S150-S160
	<u>Andrew Volcanics</u>	
11	Flows of light gray hornblende andesite. Upper portions are leached and stained red.	S265-S282
11a	Similar to above; portions of unit leached.	S340-S355
	Andesite Porphyry Domes	
4	Light gray columnar hornblende-bearing andesite collected in a road materials quarry.	S184-S195
5	Similar to above. Specimens collected from andesite exposed by road cut.	S196-S205
6	Similar to above. Andesites exposed by small quarry.	S210-216
7	Similar to above. Specimens taken from sea cliffs on east side of dome.	S217-224
	<u>Finger Bay Volcanics</u>	
3	Dark gray-green metabasalt (greenstone) and light rhyodacite flows exposed in a quarry at the south end of Clam Lagoon. Section dips northwest at 45°.	S161-S183
8	Lithic tuff breccias and flows of andesitic basalt collected in a small quarry on the south side of Andrew Lake. Section dips northwest at 50°.	S225-S237
9	Coarse grained andesite flow (?). Adjacent to site 8.	S238-S243

Table 6 continued

Site Nos.*	Description of Sites	Specimen Nos.
	Finger Bay Volcanics (continued)	
10	Andesite Sill and Palagonitic Tuff Breccia interbedded with stratified sandstones, siltstones, and shales. Section dips northwest at 45°. From same section as above.	S245-S264
10a	Interbedded basaltic pillow lavas and volcanic sediment.	S300-S337

*Sites collected during the 1968 field by Dr. Stone and Messrs. Bingham and [illegible]terjee herein denoted by "a" following the site number.

in some sections as a pseudomorph after olvine. Glomeroporphyritic clusters of pyroxene and olvine also occur infrequently.

Andesite Porphyry Domes

Hornblende Andesite: Phenocrysts of green hornblende, oxyhornblende, plagioclase, quartz, alkali feldspar and magnetite are situated in a felted matrix composed of plagioclase, alkali feldspar, quartz (often occurring as rounded, resorbed xenocrysts in rocks from the upper roof portions of the domes) and alteration and accessory minerals including Fe-oxides, epidote, chlorite, calcite apatite and tremolite-actinolite. Minor leucoxene occurs in many magnetite grains as an alteration product of exsolved ilmenite. Alteration effects within a given site vary as a function of distance from the margin or roof of the intrusive. Generally those rocks collected from the margin or roof portion of a given intrusive are only moderately altered, whereas those collected towards the centers or cores of the domes are more intensely oxidized and saussuritized. These effects are tentatively attributed to degassing phenomena which followed the emplacement of the domes in the upper crust. The frequent occurrence of quartz xenocrysts (many surrounded by reaction rims of chlorite and pyroxene) in rocks from the upper portions of the domes, indicates that only partial unroofing of these intrusives has occurred.

Finger Bay Volcanics

Metabasalt (Greenstone), Site 3. Phenocrysts and microphenocrysts of highly altered and eroded labradorite, augite, chloritized and/or serpentinized clinopyroxene and olvine (?), clinochlore, prochlorite, zeolites are set in a felted matrix of plagioclase microlites, altered clinopyroxene, magnetite, prochlorite, zeolites, minor epidote (?) and a small amount of devitrified glass.

Rhyodacite, Site 3. Phenocrysts of plagioclase (An32), quartz and alkali feldspar are set in a fine-grained matrix composed of interwoven grains of plagioclase, quartz, potassic feldspar (?), chlorite and magnetite.

Rhyodacite, Site 3. In thin section these rocks exhibit trachytic and sub-trachytic textures with parallel and sub-parallel alignment of grains due to flow. Phenocrysts of plagioclase (An30) and augite are set in an interwoven matrix consisting of plagioclase laths and microlites (albite and oligoclase), potassic feldspar, quartz, calcite, chlorite, magnetite, and interstitial devitrified glass.

Andesitic Basalt, Site 8. The rocks exhibit intersertal textures in thin section. Phenocrysts of plagioclase (An56), clinopyroxene and magnetite are set in a fine-grained felted matrix consisting of plagioclase and alkali feldspar microlites, clinopyroxene, chlorite, minor epidote (?), Fe-oxides and minor quartz.

Lithic Tuff Breccia, Site 8. Basaltic rock fragments, and phenocrysts and microphenocrysts of plagioclase, clinopyroxene and abundant magnetite are set in a fine-grained matrix consisting of plagioclase, minor alkali feldspar, quartz, zeolites, chlorite and minor amounts of devitrified volcanic glass. The basaltic rock fragments consist of phenocrysts of plagioclase, clinopyroxene and magnetite set in a matrix of dark brown devitrified glass and plagioclase microlites.

Andesite, Site 9. These rocks are relatively coarse grained and exhibit intergranular textures in thin section. Phenocrysts and microphenocrysts (comprising up to 80% of the rock) of plagioclase (An 46), clinopyroxene, magnetite, biotite, hornblende and oxyhornblende are set in a matrix consisting of plagioclase laths, prochlorite, Fe-oxides and actinolite-tremolite.

Andesite, Site 10. Phenocrysts and microphenocrysts of plagioclase, clinopyroxene and magnetite are set in a matrix consisting of interwoven plagioclase laths, prochlorite, epidote (?), biotite (?), calcite, potassic feldspar (?) and zeolites. Specimens S245-S248 were taken within 15 cm of the lower contact of the andesite body. These specimens are almost devoid of phenocrystal or microphenocrystal magnetite. On the other hand specimens taken from the main body of the andesite are relatively rich in phenocrystal magnetic oxides.

Palogonitic Tuff Breccia, Site 10. Volcanic rock fragments, and phenocrysts of plagioclase and augitic clinopyroxene are set in matrix consisting of palagonite, devitrified brown glass, zeolites, chlorite, magnetite, carbonate, epidote and minor alkali feldspar and quartz.

Basaltic Pillow Lavas, Site 10a. Phenocrysts of andesine and labradorite, clinopyroxene, and abundant magnetite are situated in a fine-grained matrix consisting of devitrified brown glass, palagonite, chlorite, plagioclase microlites, clinopyroxene, disseminated iron-titanium oxides, epidote, calcite, tremolite-actinolite and secondary quartz and zeolites.

Volcanic Sediment, Site 10a. Dark, well-bedded, iron rich clastic rocks composed of fine and very fine grains of feldspar (chiefly plagioclase), quartz, magnetite and volcanic rock fragments set in an exceedingly fine-grained matrix of clay minerals, chlorites and calcite.

Zeolites recur in seams, cavities, and occasionally along bedding planes.

Paleomagnetic Observations

The results of the measurements of Mid-Late Tertiary and Quaternary rocks are illustrated in Figs. 29-32. These data are summarized in Tables 7 and 8. Remanence data for the Finger Bay Volcanics are displayed in Figs. 33-34 and summarized in Table 9. Conventions adopted for plotting remanence directions in the previous chapter are maintained here (see p.54). Mean site susceptibilities, intensities of NRM, and Q_n-ratios are listed in Table 10 and shown graphically in Figure 35.

Late Tertiary and Quaternary Rocks

Adagdak Volcanics (Fig. 29). The specimens collected from sites 1, 1a, and 2 exhibit relatively high magnetic stabilities. As is indicated by the demagnetization curves for the pilot specimens, hard components of remanent magnetization comprise some 20-40% of the total remanence of the rocks. Hard components of magnetization in these specimens were not demagnetized in fields as high as 1000 oe (peak). The mean direction for the Adagdak volcanics was computed giving equal weight to each specimen collected at the three sites. The mean direction shifted only slightly (away from the direction of the present axial field for Adak) after demagnetization in peak fields of 375 oe. In alternating fields above 500 oe the dispersion of the vector direction of the pilot specimens tends to increase. The Q_n-ratio obtained for the sites tends to indicate the preponderance of stable components of magnetization in these rocks (Fig. 35).

Andrew Volcanics (Fig. 33). Most of the specimens collected at sites 11 and 11a are regarded as carrying substantial components of stable remanent magnetization. Soft components were removed in alternating fields of 250 oe (peak), and the mean direction for all of the specimens measured did not shift significantly after demagnetization in fields of 375 oe (peak). The vector directions of the pilot specimens tended to disperse only after demagnetization in relatively high alternating fields.

Six of the fourteen specimens collected at site 11 are somewhat leached and stained red. The demagnetization curve for a selected specimen from this group (S280b) demonstrated that very hard components of magnetization comprise virtually all of the remanence of the rock. These components are resistant to alternating fields of 1000 oe (peak). The Q_n-ratio for the 6 specimens is anomalously high. These specimens were collected from the upper portion of the flow unit at site 11. The red staining might well result from the deposition of hematite from groundwaters seeping down from the volcanogenic sediments overlying the flow unit, If so, then the observed remanence of these specimens could be attributed to a very stable secondary CRM. However, since the directions of these specimens are distributed randomly about the mean direction, along with the other specimens, no appreciable error is introduced by including them with the unaltered specimens for the purpose of computing the mean direction for the Andrew Volcanics.

Specimens S149-S155, collected at site 11a, are severely leached and almost completely calcitized. The magnetization of these specimens is very weak as is shown by the demagnetization curve for specimen S352b.

In some of the specimens the bulk susceptibility was also observed to be very low. Since the specimens are too weak to be gainfully measured with the present apparatus they were not included with the other andesites in the computation of the mean direction.

Adagdak and Andrew Volcanics, Combined Data. The combined directions of remanence in the magnetically stable rocks from the Adagdak and Andrew Volcanics are displayed in Figure 31(a). The mean directions derived for the two formations have circles of confidence which intersect; with the mean direction of one formation being very nearly included in the circle of confidence round the mean direction of the other (Fig. 31b). This implies that the mean directions do not differ significantly. The remanence data for the two formations were combined with each specimen given equal weight in the calculation of the mean direction. The mean direction obtained for the combined data is illustrated in Figure 31(b).

Mid-Late Tertiary Rocks, (Andesite Domes, Fig. 32).

Site 4. Specimens from this site have reversed polarities. Soft components of magnetization were removed in peak fields of 375 oe. A secondary soft component with a normal polarity was removed in a peak alternating field of 50 oe. The dispersion of vector directions decreased appreciably after demagnetization of the specimens in 375 oe peak fields. The mean normalized direction of magnetization rotated some 28° and steepened slightly after demagnetization.

Site 5. Specimens show normal polarities and group tightly about a mean direction which did not change after demagnetization in 375 oe peak fields of 375 oe.

Site 6. Relatively small soft components were removed in 375 oe peak fields. The site mean direction shifted slightly after demagnetization in peak fields of 375 oe. The specimens are reversely magnetized. A secondary soft component with a polarity opposite to that of the dominant magnetization of the rocks was removed in 50 oe peak fields.

Site 7. Specimens from this site also show reversed polarities but the demagnetization curves for pilot specimens indicates that there has been no build-up of soft secondary components. Hard components of magnetization comprise virtually all of the remanent magnetization of the rocks. The site mean direction shifted only slightly after demagnetization in peak fields of 375 oe.

From the behavior of the remanent magnetization the specimens from the andesite intrusives are considered magnetically stable. Hard components of magnetization could not be demagnetized in alternating fields as high as 1000 oe (peak). At the 95% confidence level, none of the site mean directions include the direction of the present axial field for Adak. Demagnetization of the specimens in 375 oe peak fields generally served to improve both the within-site and between-site dispersion of vector directions. The mean Q_n-ratios for the respective sites also indicate the presence of stable components in the specimens.

Although a significant decrease in the dispersion of site mean directions occurred after treatment of the specimens in alternating fields, the error limits round the mean directions for the various sites do not overlap. On the basis of this criteria, the mean directions of remanent magnetization of the andesite intrusives are considered to differ significantly, and no attempt was made to combine them. Possible explanations for the behavior of the site mean directions in the andesite domes are reviewed in the concluding section of this chapter.

Eocene Rocks, (Finger Bay Volcanics, Figs. 33-34, Table 9).

The paleomagnetic signature of the Finger Bay Volcanics can be summarized as follows:

1. The rocks are generally less intensely magnetized than those from the Mid-Late Tertiary and Quaternary sites (see Table 10 and Fig. 35). Some specimens were unable to withstand high-field demagnetization and still remain strong enough for remeasurement.

2. Soft components comprise much of the remanent magnetization and were generally erased in 100-200 oe peak alternating fields (Fig. 33). Specimens from site 9 may be exceptional in this regard. The stepwise character of the demagnetization curve for pilot specimen S242 possibly indicates the presence of two types (and hence, perhaps two generations) of soft components. The lower coercivity component was removed in peak fields of 100 oe. A second, higher coercivity component was removed in peak fields of 400 oe. Optimum grouping of vector directions at site 9 was achieved after demagnetization in 400 oe peak fields.

3. Several pilot specimens (S231, S227, S260, in Fig. 33), acquired small but significant magnetizations during stepwise demagnetization and remeasurement which are most easily explained by anhysteresis.

4. The dispersions of vector directions, as indicated by the circles of confidence round mean site directions in Fig. 24, are in most cases significantly greater than those in Mid-Late Tertiary and Quaternary sites on Northern Adak.

5. Mean Q_n-ratios for most of the older sites are considerably lower than those obtained for the younger sites (Fig. 35), and indicate the presence of substantial unstable components of magnetization.

Eighteen specimens from two sites were not included in the computation of mean site directions. Very weak specimens, collected from a rhyodacite flow at site 3, (S177-S181), gave highly scattered directions with mixed polarities and a mean Q_n-ratio which indicates that the rocks are largely unstable. Specimens S245-S248, collected from the contact phase of the andesite sill at site 10 were too weak to measure accurately and also have very low Q_n-ratios. Palagonitic tuff breccias, (S256-S264), collected at site 10 are very weak, have a low Q_n-ratio, and gave highly dispersed directions.

The remaining specimens, totaling some 77 cores from 5 sites, are regarded as carrying both stable and unstable components of magnetization. Treatment of the specimens in alternating fields tended to improve groupings of vector directions at some sites and indicates the removal of a portion of the unstable components.

Viscous decay of primary remanent magnetization is probably responsible for the low initial intensities of these rocks since magnetic oxides are abundant, both as a phenocrystal and matrix phase, in most of the thin sections studied, and mean site susceptibilities are relatively high. Magnetic oxides are only moderately altered, however exsolved ilmenite, (altered to leucoxene) occurs in most of the magnetite of these rocks.

Mean site directions of magnetization are illustrated in Fig. 34. Only the error circle round the mean of site 3 includes the direction of remanent magnetization for the Finger Bay Volcanics Formation.

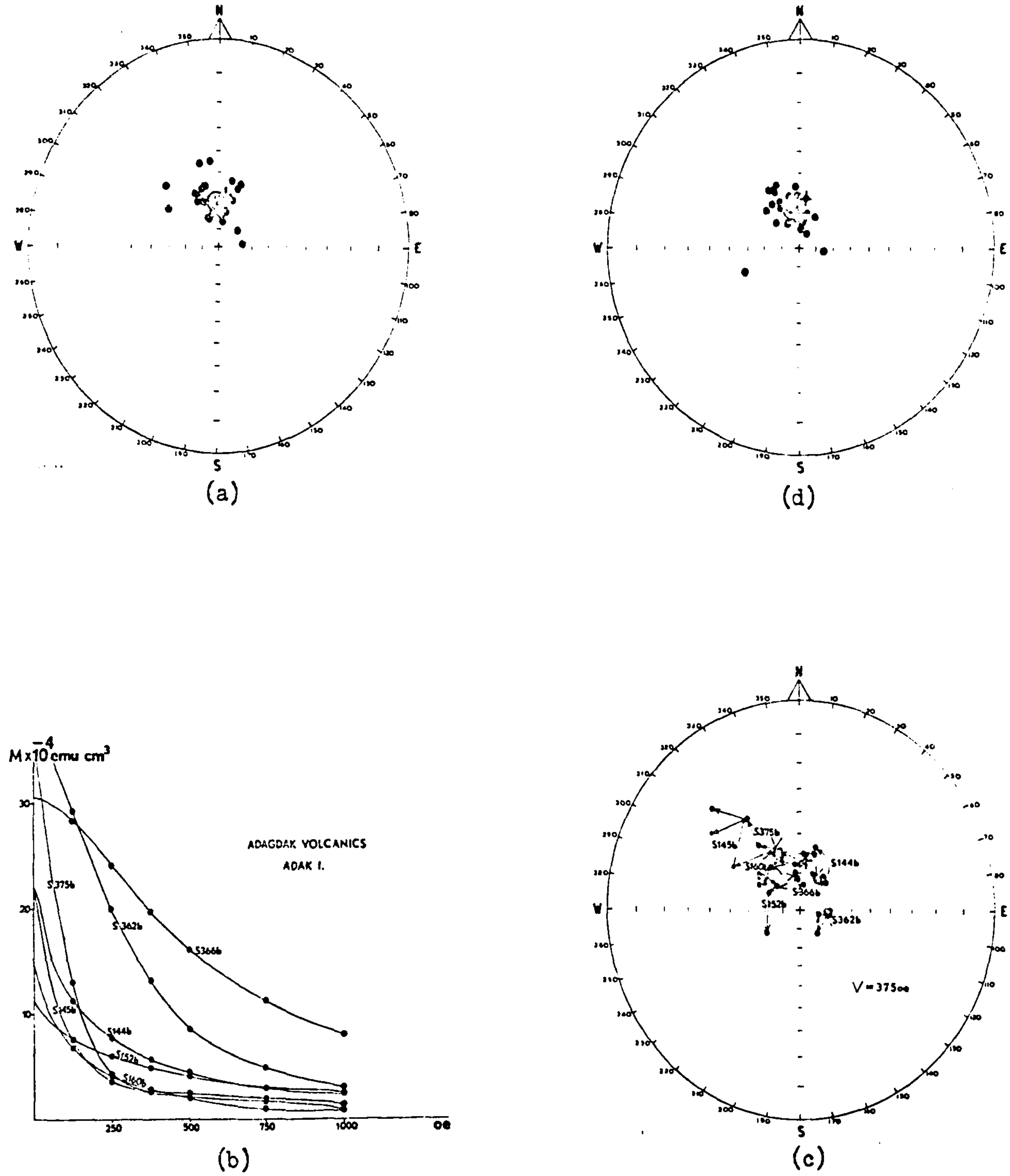


Figure 29. Directions of remanent magnetization and effect of alternating field demagnetization in Adagdak Volcanics. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vector directions in pilot specimens during treatment in alternating fields. (d) Directions of remanent magnetization after treatment of specimens in peak alternating fields of 375 oe. The (+) indicates the present direction of the axial dipole field.

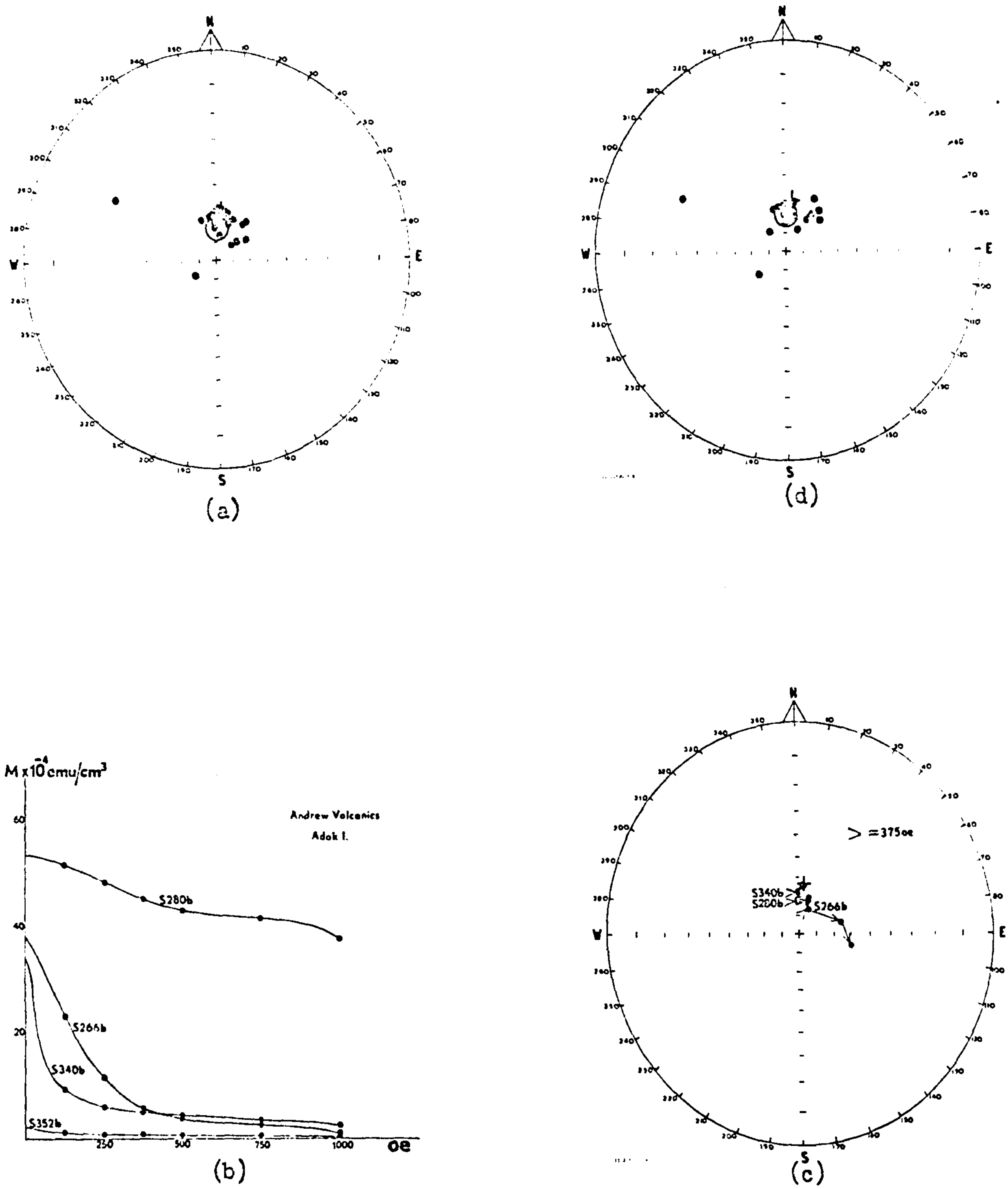


Figure 30. Directions of remanent magnetization and effect of alternating field demagnetization in Andrew Volcanics. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vector directions in pilot specimens during treatment in alternating fields. (d) Directions of remanent magnetization after treatment of the specimens in peaks alternating fields of 375 oe. The (+) indicates the present direction of the axial dipole field.

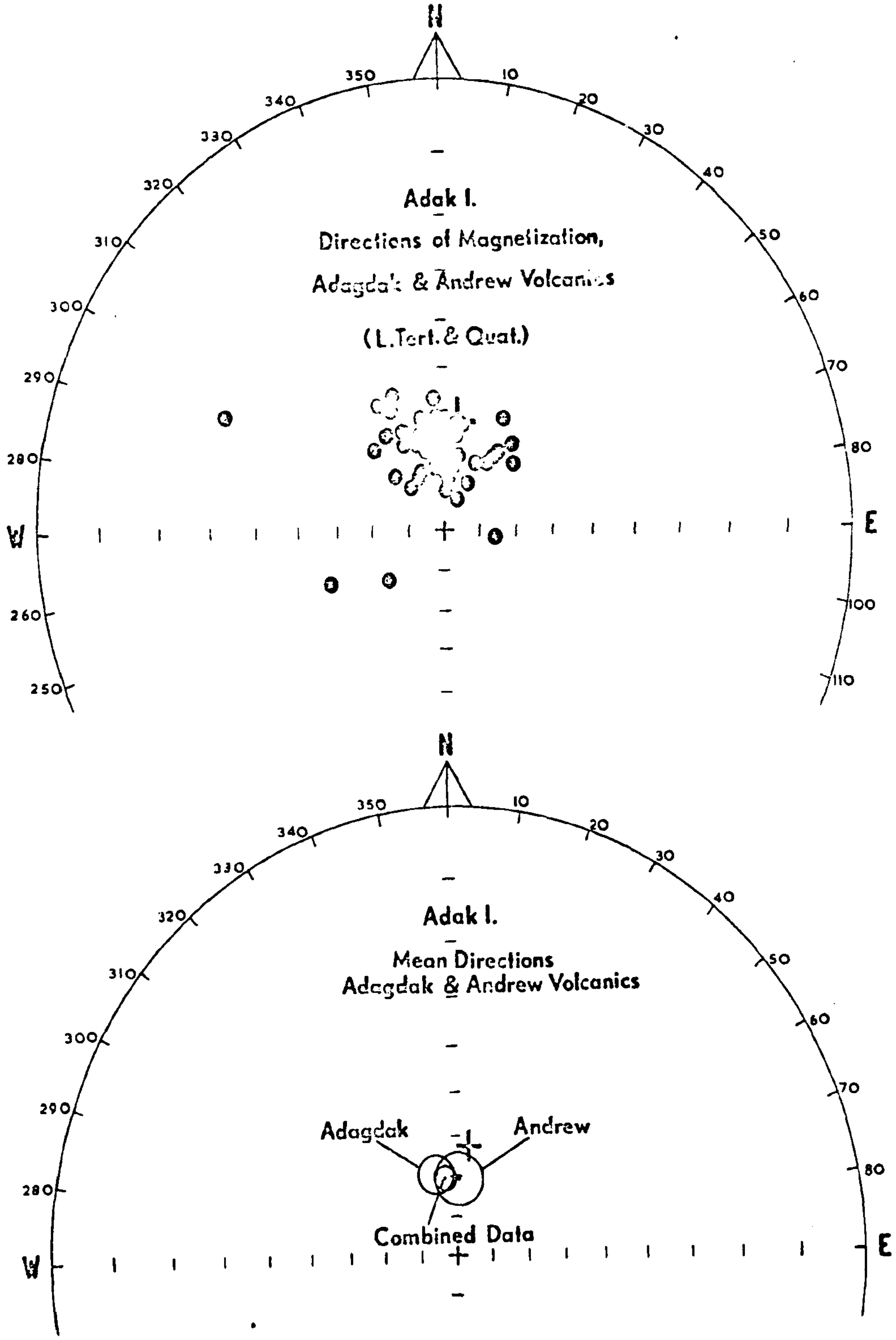


Figure 31. Directions of remanent magnetization, Adagdak and Andrew Volcanics, (combined data). The (+) indicates the present direction of the axial dipole field.

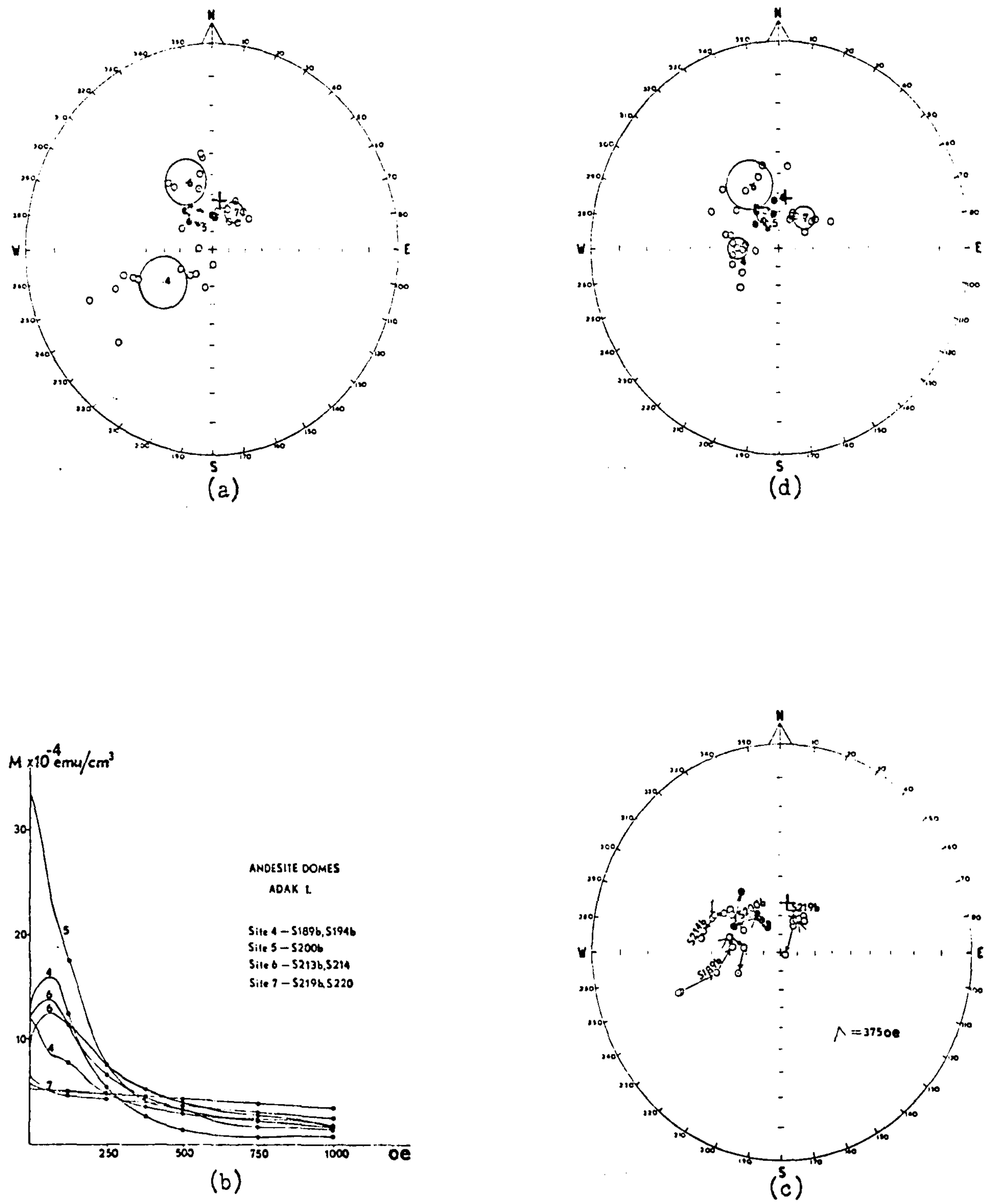


Figure 32. Direction of remanent magnetization and effect of alternating field demagnetization in Andesite Domes. (a) NRM. (b) Demagnetization curves of pilot specimens. (c) Behavior of vector directions in pilot specimens during treatment in alternating fields. (d) Directions of remanent magnetization after treatment of specimens in peak alternating fields of 375 oe. The (+) indicates the present direction of the axial dipole field.

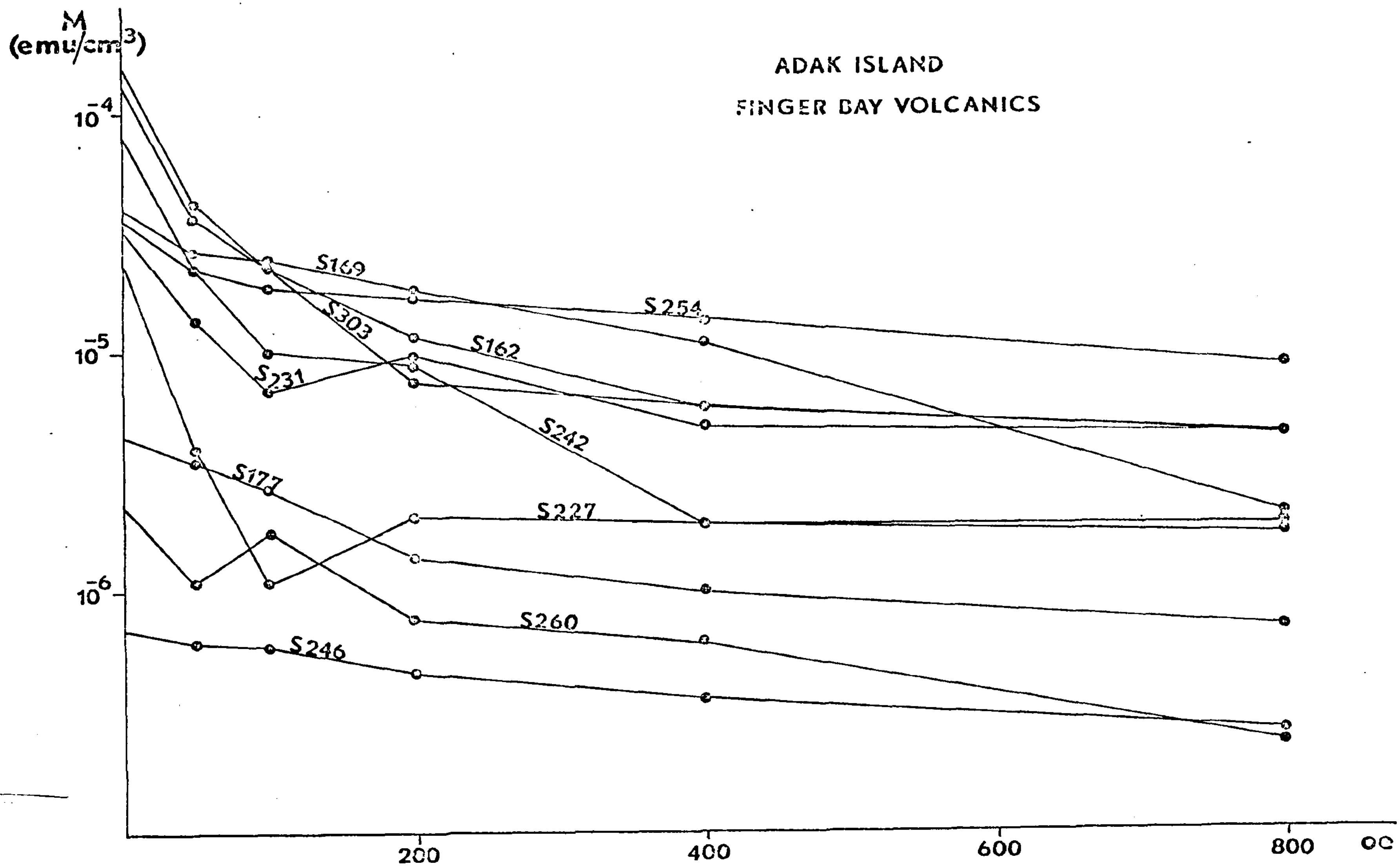


Figure 33. Demagnetization curves of pilot specimens, Finger Bay Volcanics.

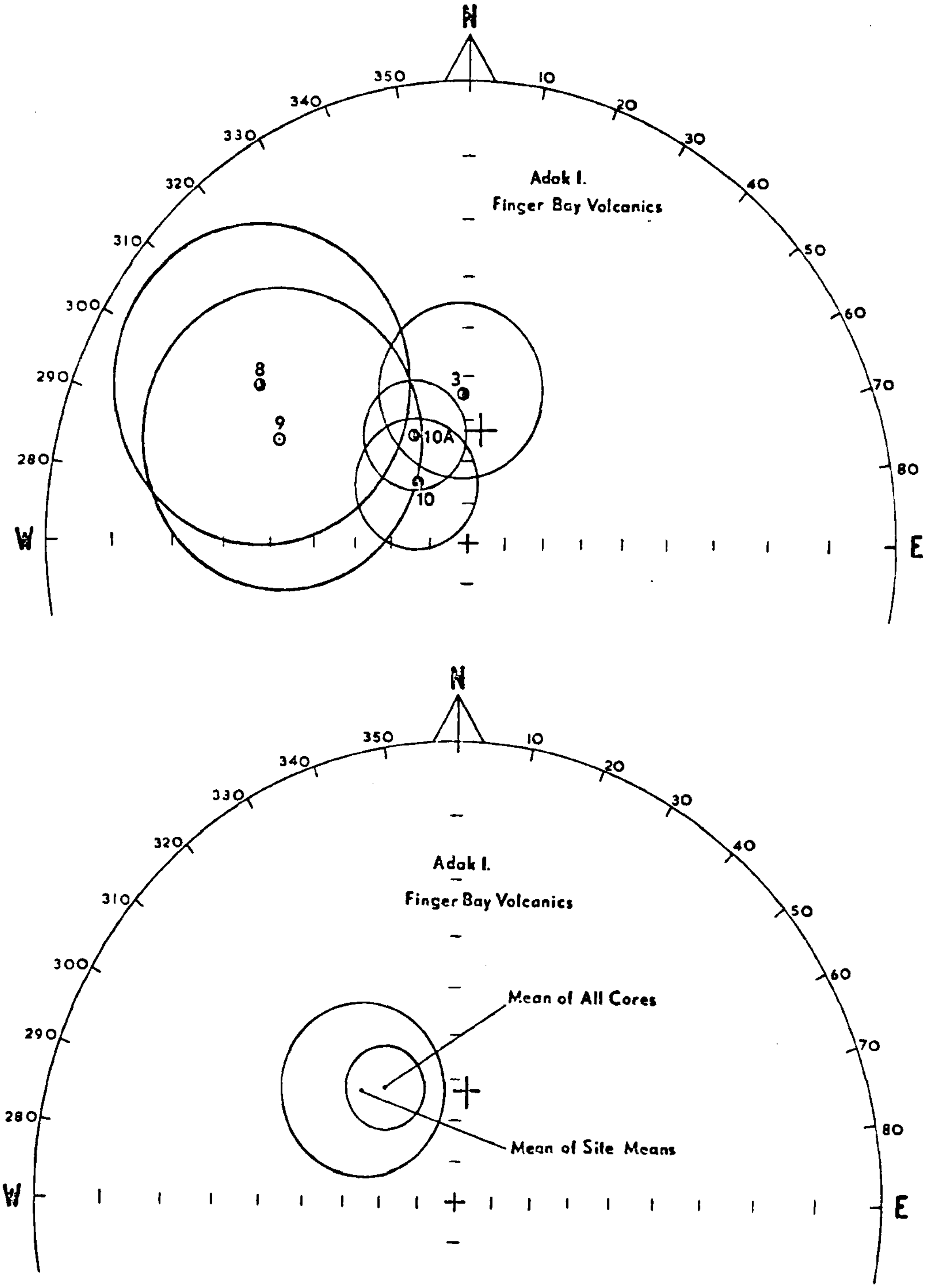


Figure 34. Directions of remanent magnetization, Finger Bay Volcanics. Half-open symbols indicate sites with both normally and reversely polarized rocks. The (+) indicates the present direction of the axial dipole field.

Table 7.

Mean directions of NRM, pole positions, and associated statistics for Late Tertiary and Quaternary sites from Northern Adak Island

Site No.	Lat. (°N)	Long. (°E)	N	R	D_m (°ETN)	I_m (°down)	k	α_{95}	P_{lat} °N	P_{long} °E	δ_p	δ_m	Polarity
Adagdak Volcanics													
1	51.96	176.57	10	9.829	6.59	62.62	52.8	6.7	81.0	331.7	8	10	N
1a	51.96	176.57	18	17.790	358.09	68.72	80.8	3.9	88.8	103.4	6	7	N
2	51.95	176.57	10	9.735	339.46	57.63	34.0	8.4	70.2	57.9	9	13	N
Andrew Volcanics													
11	51.96	176.62	14	13.314	347.16	71.10	19.0	9.4	81.6	124.5	14	16	N
11a	51.97	176.63	9	8.870	31.47	70.90	61.4	6.6	71.2	250.5	10	11	N
Andesite Domes													
4	51.86	176.64	12	10.926	60.88	-54.67	10.2	14.3	12.0	136.5	15	20	R
5	51.88	176.64	10	9.949	335.14	70.29	176.0	3.7	75.0	112.7	6	6	N
6	51.92	176.56	7	6.802	156.23	-50.39	30.2	11.2	62.9	52.6	11	15	R
7	51.91	176.56	8	7.935	211.99	-65.52	108.4	5.3	69.1	272.2	6	9	R
Mean Adagdak Volcanics			38	37.105	354.48	64.63	41.3	3.7	83.5	39.4	4	6	N
Mean Andrew Volcanics			23	22.023	4.76	72.28	22.5	6.5	83.8	208.0	10	11	N

N = number of specimens; R = length of vector sum of N unit vectors; D_m, I_m = estimate of mean direction of magnetization; k = precision parameter for D_m, I_m; α_{95} = radius of circle of confidence at 95% level for D_m, I_m; P_{lat}, - P_{long} = latitude and longitude of paleomagnetic pole; δ_p, δ_m = semi-axes of the elliptical error round the pole at a probability of 95%: Polarity (N = Normal, R = Reversed, M = Mixed); AF = alternating field in oersteds.

Table 8.

Mean directions of magnetization, pole positions, and associated statistics for Late Tertiary and Quaternary sites from Northern Adak Island after treatment in alternating fields

Site No.	Lat. °N.	Long. °W	N	R	D_m (°ETN)	I_m (°down)	k	α_{95}	P_{lat} °N	P_{long} °E	δ_p	δ_m	Polarity	AF (oe)
Adagdak Volcanics														
1	51.96	176.57	10	9.867	359.77	71.82	67.7	5.9	85.2	181.8	9	10	N	375
1a	51.96	176.57	18	17.742	351.97	68.82	65.9	4.3	85.1	100.4	6	7	N	375
2	51.95	176.57	10	9.700	325.95	64.32	30.0	9.0	67.2	92.3	12	15	N	375
Andrew Volcanics														
11	51.96	176.62	14	13.367	347.63	69.81	20.6	9.0	82.3	111.6	13	15	N	375
11a	51.97	176.63	9	8.837	26.64	68.54	49.2	7.4	73.6	263.0	10	12	N	375
Andesite Domes														
4	51.86	176.64	12	11.783	88.56	-65.53	50.7	6.2	34.9	128.3	8	10	R	375
5	51.88	176.64	10	9.918	334.71	69.87	110.1	4.6	74.7	110.3	7	8	N	375
6	51.92	176.56	7	6.739	153.33	-52.57	23.0	12.9	63.2	59.5	13	18	R	375
7	51.91	176.56	8	7.918	222.90	-67.67	85.6	6.0	63.5	259.0	8	9	R	375
Mean Adagdak Volcanics			38	37.130	345.82	68.99	42.5	3.6	81.3	102.7	5	6	N	375
Mean Andrew Volcanics			23	22.053	3.57	70.37	23.2	6.4	86.6	221.4	10	11	N	375
Mean Adagdak + Andrew Volcanics			61	59.099	352.15	69.71	31.6	3.3	85.0	115.3	5	7	N	375

N = number of specimens; R = length of vector sum of N unit vectors; D_m, I_m = estimate of mean direction of magnetization; k = precision parameter for D_m, I_m; α_{95} = radius of circle of confidence at 95% level for D_m, I_m; P_{lat}, P_{long} = latitude and longitude of paleomagnetic pole; δp, δ_m,= semi-axes of the elliptical error round the pole at a probability of 95%; Polarity (N=Normal, R=Reversed, M=Mixed); AF = alternating field in oersteds.

Table 9.

Mean directions of magnetization, pole positions, and associated statistics for Eocene sites (Finger Bay Volcanics) from Northern Adak Island after treatment in alternating fields

Site No.	Lat. °N	Long. °W	N	R	D_m (°ETN)	I_m (°down)	k	α_{95}	P_{lat} °N	P_{long} °E	δ_p	δ_m	Polarity	AF (oe)
Finger Bay Volcanics														
3	51.94	176.60	16	12.354	356.60	52.02	4.1	20.8	70.6	12.0	19	28	M	200
8	51.92	176.64	13	8.639	304.26	32.39	2.8	31.0	34.7	76.7	21	36	N	150
9	51.92	176.64	6	5.127	296.11	40.56	5.7	30.7	34.0	88.1	24	37	R	600
10	51.93	176.63	7	6.613	314.01	70.48	15.5	15.8	62.9	117.6	24	27	N	400
10a	51.94	176.63	35	28.122	331.08	59.91	4.9	12.2	67.4	75.5	15	19	M	2-300
Mean of Site Means Finger Bay Volcanics			5	4.722	317.82	53.22	14.4	20.9	54.8	79.1	21	29	M	150-600
Mean of all cores Finger Bay Volcanics			77	58.412	326.03	55.72	4.1	9.2	61.4	73.7	10	13	M	150-600

N = number of specimens; R = length of vector sum of N unit vectors; D_m, I_m = estimate of mean direction of magnetization; k = precision parameter for D_m, I_m; α_{95} = radius of circle of confidence at 95% level for D_m, I_m; P_{lat}, P_{long} = latitude and longitude of paleomagnetic pole; δ_p, δ_m = semi-axes of the elliptical error round the pole at a probability of 95%; Polarity (N = Normal, R = Reversed, M = Mixed); AF = alternating field in oersteds.

Table 10. Mean Site Susceptibilities, Intensities of Nrm and Q_n-Ratios, Northern Adak Island

Site No.	N	K (emu/cm^3)	M_{nrm} (emu/cm^3)	Q_n	Rock Type
Late Tertiary and Quaternary Rocks					
1	10	4.64×10^{-3} (0.89)	1.64×10^{-3} (0.38)	0.39	Olivine Basalt
1a	12	4.59×10^{-3} (0.96)	3.73×10^{-3} (0.83)	0.81	Olivine Basalt
1a	6	1.75×10^{-3} (0.50)	3.19×10^{-3} (0.50)	1.82	Vesicular Olivine Basalt
2	10	4.14×10^{-3} (1.46)	1.49×10^{-3} (0.17)	0.40	Andesitic Basalt
4	12	3.86×10^{-3} (0.40)	1.01×10^{-3} (0.25)	0.26	Hornblende Andesite
5	10	4.48×10^{-3} (0.41)	4.49×10^{-3} (2.10)	1.00	Hornblende Andesite
6	7	3.94×10^{-3} (0.17)	0.94×10^{-3} (0.27)	0.24	Hornblende Andesite
7	8	3.57×10^{-3} (0.34)	1.27×10^{-3} (0.70)	0.36	Hornblende Andesite
11	8	2.27×10^{-3} (0.21)	4.29×10^{-3} (1.16)	1.89	Hornblende Andesite
11*	6	0.21×10^{-3} (0.11)	5.07×10^{-3} (0.77)	24.14	Leached Hornblende Andesite with Iron Oxide staining (Red)
11a	9	5.16×10^{-3} (0.66)	3.27×10^{-3} (1.02)	0.63	Hornblende-bearing Basaltic Andesite
11a*	2	1.94×10^{-3} (NA)	0.12×10^{-3} (NA)	0.06	Severely leached Hornblende Andesite
11a*	5	0.08×10^{-3} (0.02)	0.03×10^{-3} (0.02)	0.38	Severely leached Hornblende Andesite
Eocene Rocks (Finger Bay Volcanics)					
3	7	5.24×10^{-3} (0.35)	1.04×10^{-3} (0.17)	0.20	Metabasalt (Greenstone)
3	9	1.58×10^{-3} (0.14)	0.40×10^{-3} (0.07)	0.25	Rhyodacite
3*	5	1.48×10^{-3} (0.24)	0.05×10^{-3} (0.02)	0.03	Rhyodacite
8	13	5.46×10^{-3} (0.99)	0.58×10^{-3} (0.25)	0.11	Altered Andesite and Lithic Tuff Breccias
9	6	5.92×10^{-3} (0.50)	0.54×10^{-3} (0.22)	0.09	Andesite
10	7	3.37×10^{-3} (0.61)	0.45×10^{-3} (0.13)	0.13	Andesite
10*	4	0.37×10^{-3} (0.17)	0.03×10^{-3} (0.01)	0.08	Andesite, (contact phase)
10*	9	0.56×10^{-3} (0.20)	0.03×10^{-3} (0.10)	0.05	Palagonitic Lithic Tuff Breccia
10a	22	6.12×10^{-3} (0.44)	1.50×10^{-3} (0.27)	0.25	Basaltic Pillow Lavas
10a	6	0.12×10^{-3} (0.07)	0.05×10^{-3} (0.02)	0.42	Volcanic Sediment
10a	7	2.24×10^{-3} (0.28)	0.41×10^{-3} (0.30)	0.18	Volcanic Sediment

K = Mean low-field bulk susceptibility; arithmetic mean standard deviation in brackets.
M_{nrm} = Mean intensity of NRM; arithmethic mean standard deviation in brackets.
$Q_n^{nrm} = M_{nrm}/K$.

* Magnetically unstable rocks; were not used in computation of the mean direction for the site.

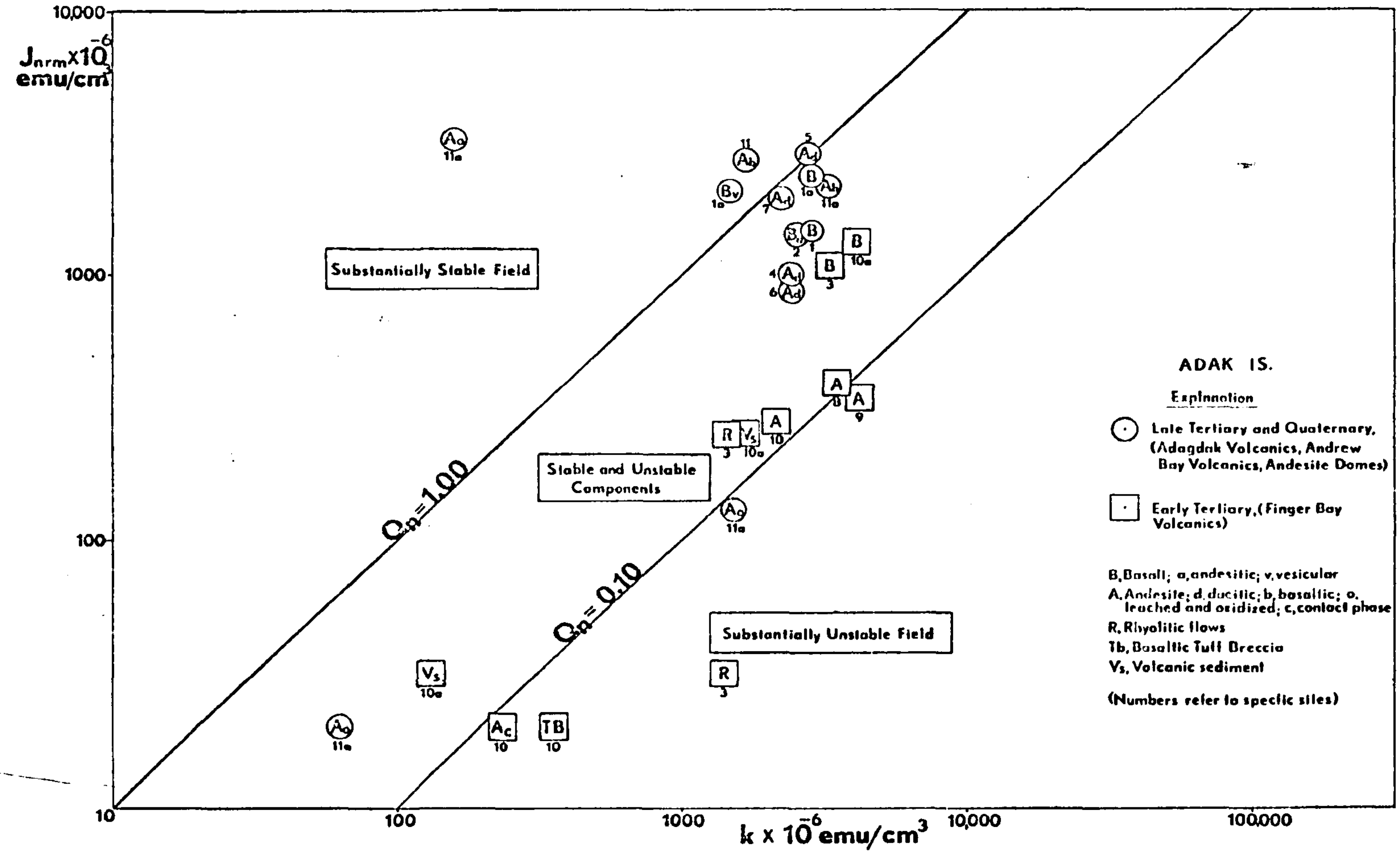


Figure 35. Relation between intensity of NRM and bulk magnetic susceptibility in Tertiary and Quaternary rocks from Adak Island.

Discussion of Results

Mid-Late Tertiary and Quaternary rocks from Northern Adak satisfy the following generally accepted criteria of magnetic stability:

1. Site mean directions of magnetization diverge significantly from the direction of the present axial dipole field for Adak, indicating that the rocks are able to maintain a magnetization other than that imposed by the present or recent field.

2. Directions of magnetization which remain relatively fixed after treatment of the specimens in high alternating-field treatment.

3. The indicated presence of hard components of magnetization which cannot be demagnetized in peak alternating fields of 1000 oe.

4. Q_n-ratios whose values indicate the presence of stable components of magnetization in the rocks.

Generally, mean Q_n-ratios for sites on Northern Adak follow the pattern observed in rocks from Shemya Island. Young relatively unaltered rocks which have substantial hard components of remanent magnetization, are associated with relatively high Q_n-ratios and apparent magnetic stability (Fig. 35). Older, more altered and deformed rocks, whose primary magnetizations have been weakened by viscous decay, have generally lower Q_n-ratios and exhibit signs of magnetic instability.

Mean site directions in Tertiary and Quaternary rocks on Northern Adak are illustrated in Fig. 36. With the exception of the Andesite Domes (sites 4, 5, 6 and 7) mean site directions for the various units exhibit some degree of consistancy. However, in the case of the Andesite Domes, considerable differences in directions between sites occur over relatively short distances, especially with respect to vector declinations.

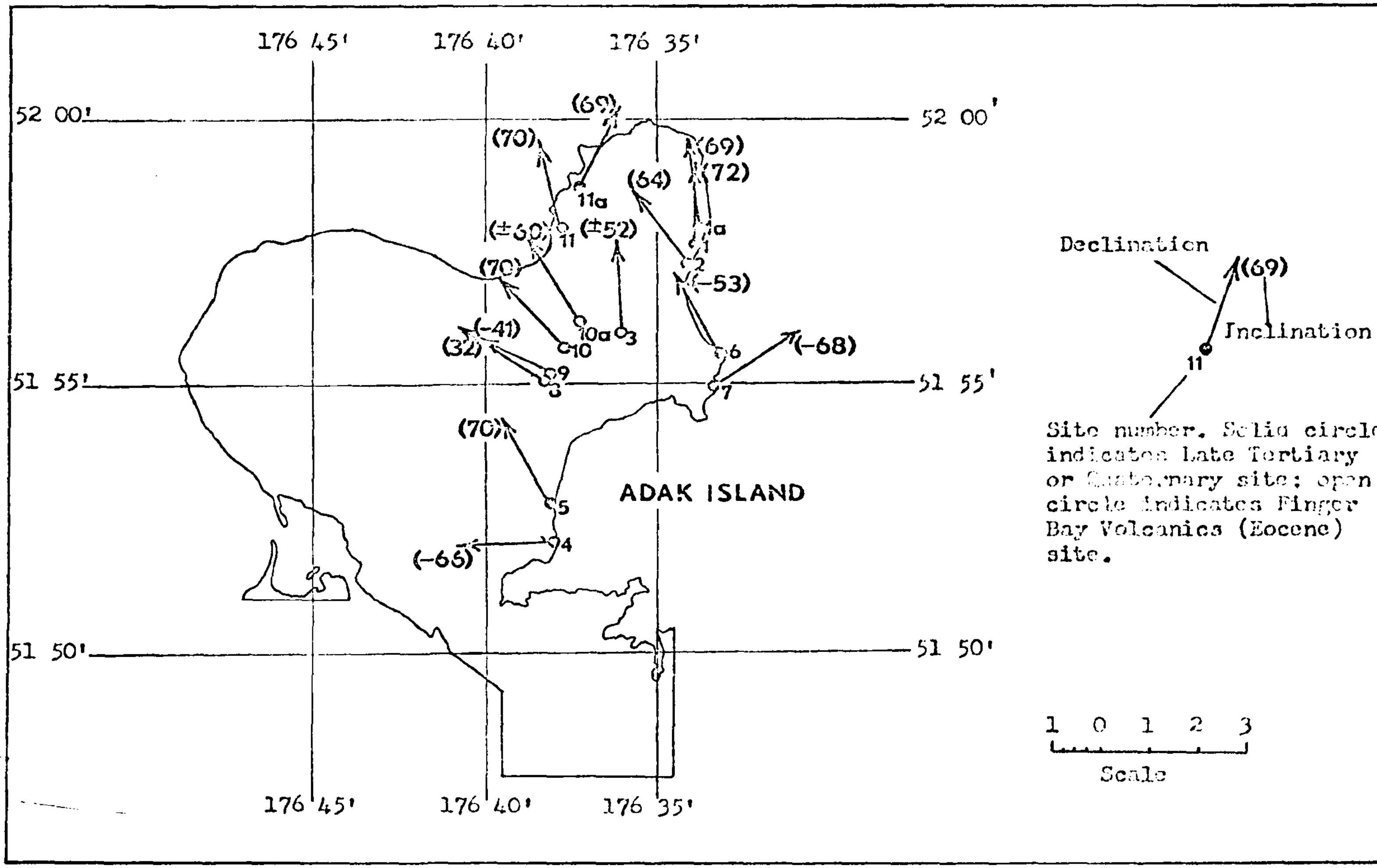


Figure 3.6. Paleomagnetic directions in Tertiary and Quaternary rocks on Northern Adak Island. Site mean declinations are given by the arrow. Mean inclinations are given in brackets next to heads of the arrows.

There exist several possible explanations which might account for the anomalous behavior of the remanent magnetization:

1. Structural dislocations in the immediate area of the intrusives which might result in physical displacement of their directions of remanent magnetization. This displacement would have to be largely rotational.

2. Physiochemical mechanisms which altered the primary remanent magnetization to the extent that it no longer accurately reflects the sense and direction of the ambient field at the time of the origin of the rocks.

3. Magnetostrictive effects, resulting from the application of nonhydrostatic stresses on the intrusives during the acquisition of their magnetization, causing rotations of the remanence vectors at some of the sites.

4. Emplacement of the domes during a polarity transition period, (i.e. as the main field was undergoing a polarity reversal).

5. Excursions of the main dipole field about its mean position during the time of formation of the rocks and their acquisition of remanent magnetization.

Of these six possibilities (1) and (2) can be dismissed as highly improbable. Nothing in the geology or topography of Northern Adak suggests deformation on the scale required to physically rotate the remanence through changes in declination of 90° or more, especially in view of the relatively small seperations between sites. There is no evidence in the petrography, nor in the experimental results of the paleomagnetic analyses, to indicate that drastic physiochemical changes have affected these rocks. The initial intensities of these specimens are relatively high which is opposite to what one might expect if such changes had occurred. Physiochemical alterations generally result in the nucleation and growth of new magnetic oxides and the deposition of secondary components of magnetization. In young rocks these components will reflect the sense and direction of the recent geomagnetic field. The wide dispersion of site mean remanence directions and their deviation from the position of the present axial field indicates that the intrusives have not been remagnetized in the Late Tertiary or Quaternary field.

It is somewhat unlikely that magnetostrictive effects could cause the differences in mean site directions. Graham (1956) suggests that the scattered magnetization of the Karroo dolerite sills is due to the presence of nonhydrostatic stresses acting during the acquisition of remanent magnetization. He postulates that the release of these stresses caused changes in the direction and intensity of the initial magnetization. However, it is difficult to maintain large nonhydrostatic pressure differentials in material much above the Curie temperature of magnetite. The experiments of Graham et.al., (1957) on metamorphic rocks from the Adirondacks, indicate that irreversible changes in remanent magnetization can be produced by isothermal application of axial compressive stress. It has also been determined that magnetite can acquire a Piezo-Remanent Magnetization or PRM simply by isothermal axial compression in the geomagnetic field; the direction of PRM being always found in the plane perpendicular to the applied stress (Domen, 1957). However, the experimental observations of Kume (1962) and others shows these effects to be generally small, unless the material is highly anisotropic, which is not the case for the domes. Since specimens from the Andesite Domes were taken from the roof portions of the intrusives, magnetostrictive effects on the remanent magnetization cannot be ruled out at this time, but would seem quantitatively unlikely.

It is possible that the between-site scatter of vector directions is due to the emplacement of the domes during a polarity transition period, especially since one of the domes has a polarity opposite to that of the others. Dispersed directions of remanent magnetization are to be expected if, in the process of reversing itself, the main field attenuates to the extent that the secular variation field becomes dominant. However, if such a phenomenon was acting during the emplacement of the andesite intrusives then the intensities of the remanent magnetization should be lower than those actually observed.

Perhaps the simplest explanation for the between-site scatter of vector directions is that they are due to excursions of the main field about its mean position during the Late Tertiary. In this context it should be noted that while the data are as yet somewhat inconclusive, some apparently stable Pliocene volcanics from other portions of the Chain and from the Wrangell Mountains tend to give similarly anomalous remanence directions, as do a number of other sites throughout the world, (D. B. Stone, personal communication).

The experimental evidence indicates that viscous effects have appreciably altered the primary magnetization of many of the Finger Bay Volcanics. There is some doubt as to the extent of the build-up of secondary components in these rocks and to what degree the investigators were able to remove them by alternating field demagnetization techniques. In some cases the accuracy of the measurements of very weak specimens was probably influenced by the limitations of the measuring device and by anhysteretic effects. There is also some doubt as to the actual age of some of the igneous units sampled.

On the other hand, the mean direction obtained for the Finger Bay Volcanics is strongly influenced by specimens from sites 10 and 10a. The dispersion of vector directions in these specimens, which comprise over half of the total number measured, is appreciably lower than that of specimens from other sites. The Q_n-ratios for sites 10 and 10a are also significantly higher than those from other Early Tertiary sites. Finally, the mean direction obtained for the Finger Bay Volcanics is significantly different than that of the present axial dipole field for Adak.

Until such time as more data are available for the early marine series in this portion of the Aleutian Chain, the mean direction of magnetization for the Finger Bay Volcanics and the paleomagnetic pole position derived from it must be treated with caution.

The relatively young age obtained for the andesite at site 10 (5.1 million years) implies that the body occurs as a sill. The Finger Bay Volcanics section on Northern Adak dips homoclinally northwestward at 45°. The directions plotted in Figure 34 have been corrected for this amount of structural tilt. If emplacement of the andesite sill took place as a post-deformation event then the inclination of the vector direction for the site would have to be rotated 45° upward in a northwesterly direction. This would effectively displace the vector from its relatively close association with the vector directions at the other sites by a considerable amount. Further, such a displacement would result in a highly anomalous pole position for a Late Tertiary rock, (neglecting the possibility of field excursions to account for the anomalous remanence). It is therefore concluded (on the grounds that it is the simplest explanation of the observation), that the unit was emplaced during a pre-deformation event and that the deformation of the Finger Bay Volcanics took place during Latest Tertiary or Quaternary times.

The pole positions for Tertiary and Quaternary units on Northern Adak are illustrated in Fig. 37. The possible implications of these data are discussed in the concluding chapter of this report.

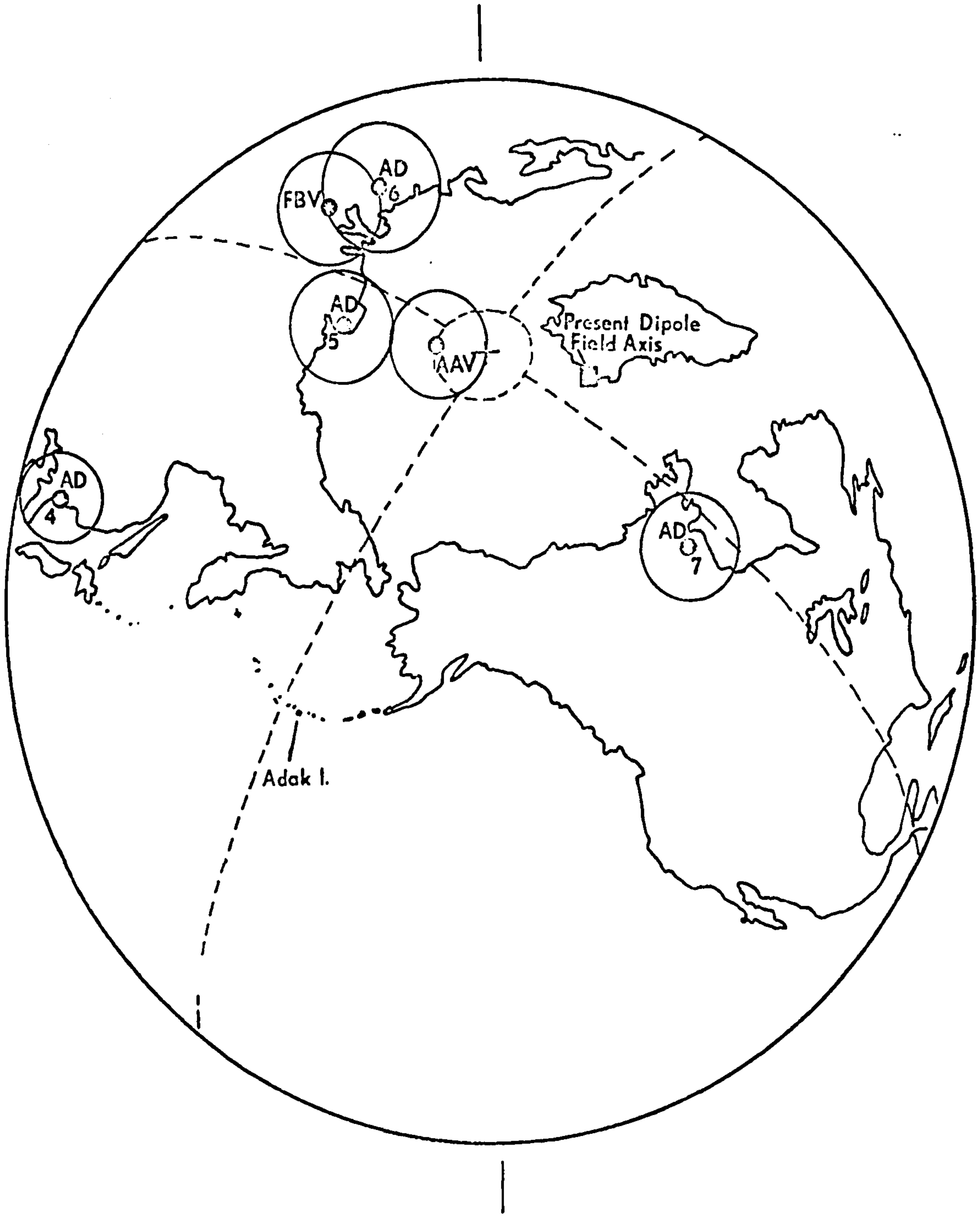


Figure 37. Pole positions determined from Tertiary and Quaternary volcanic rocks from Adak Island. AAV = Adagdak and Andrew Volcanics (Quaternary); AD = Andesite Domes (Pliocene ?), numbers refer to specific sites; FBV = Finger Bay Volcanics (Eocene).

CHAPTER V

CONCLUSIONS AND FUTURE WORK

Interpretation of Paleomagnetic Results

As has already been indicated, Mid-Late Tertiary and Quaternary volcanic rocks from Shemya and Adak Islands satisfy several criteria of magnetic stability, (see pp. 81,116). Minor soft components of secondary origin identified in several of the reversed specimens were removed in peak alternating fields of 50-100 oe. Hard components of magnetization, comprising substantial proportions of the total remanence of the rocks, were resistant to high alternating fields. The high magnetic stabilities, and the relatively unaltered state of the rocks, indicates that the remanent magnetization is probably of thermoremanent origin.

The relative lack of coherent remanence directions in the Eocene rocks studied suggests the presence of unstable components of magnetization. The low initial intensities of these specimens, as well as their highly altered state, indicate that considerable decay of the primary remanent magnetization has occurred. The character of the demagnetization curves for several of the pilot specimens from Eocene sites on Adak and Shemya establish the presence of secondary components of magnetization, some of which were not removed until after demagnetization in peak fields of 500 oe. In the case of the Eocene specimens from Shemya, it is doubtful that the weak primary component, isolated after treatment in peak fields of 250-500 oe, is of sufficient strength to measure accurately with the present equipment. From the standpoint of the present results, the remanent magnetization of the Finger Bay Volcanics can only be regarded as marginally stable.

Variations of the ratio, M_{nrm}/k, reinforce the conclusions drawn regarding the magnetic stability of the various sites studied. The variation in mean site susceptibilities and initial intensities for Shemya and Adak Islands are shown in Figure 38. With the exception of the leached and calcified specimens of hornblende andesite from site 11a, Adak, all Mid-Late Tertiary and Quaternary sites have Q_n-ratios relatively near, or greater than, 1.0. Specimens from sites 4 and 6, Adak Island show the largest departure from this ratio of all the younger rocks tested, with Q_n-ratios of 0.26 and 0.24 respectively. According to the empirical criteria cited by Irving (1964) these values signal the presence of small, unstable components of secondary magnetization. The demagnetization curves for pilot specimens from these sites establish the presence of a low-coercivity secondary component of magnetization whose polarity is opposite to that of the dominant magnetization of the specimens. The removal of the secondary component in relatively low alternating fields caused the directions of magnetization to shift significantly and the dispersion to decrease considerably, indicating the isolation of the stable TRM components, (Fig. 32).

As can be seen in Figure 38, most of the older rocks tested in the course of this investigation yielded significantly lower Q_n-ratios. This is consistant with the pattern developed during treatment of the Eocene rocks in alternating fields, which indicates the presence of substantial components of unstable magnetization. Exceptions to this trend were observed in basaltic pillow lavas and volcanic sediments from site 10a, Adak; whose behavior in alternating fields and small dispersion of vector

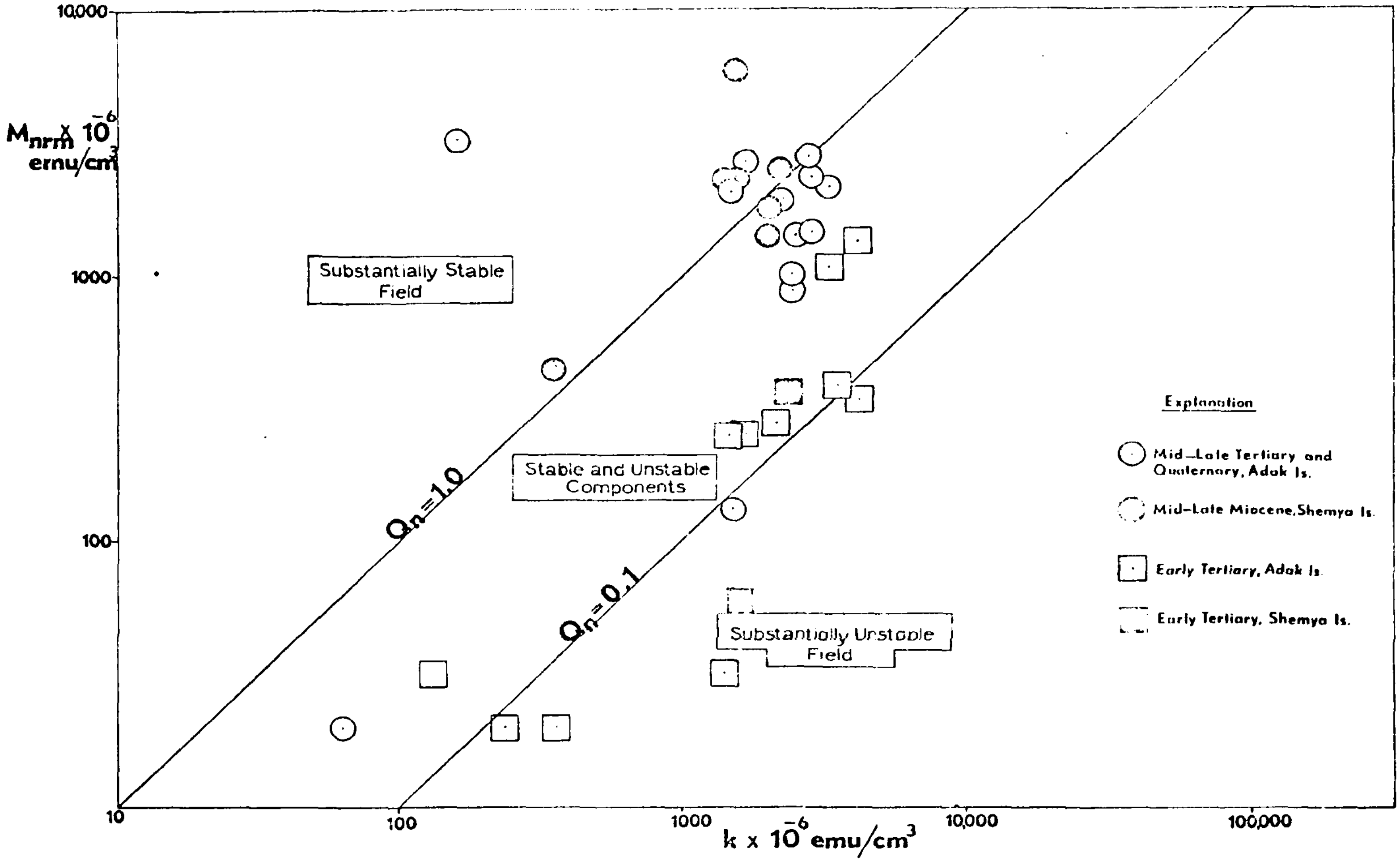


Figure 38. Relation between initial intensity of magnetization and bulk magnetic susceptibility in Tertiary and Quaternary rocks from Shemya and Adak Islands.

directions indicates the presence of relatively large stable components of magnetization, (Figs.33, 34). It will be noted that (not coincidentally),specimens from site 10a also gave the highest Q_n-ratios of all the older rocks tested, (Fig. 35).

The relation between bulk susceptibility and initial intensity of the rocks examined provides suggestive evidence as to the cause of the generally lower magnetic stabilities of the Eocene specimens. Differences in the ratio M_{nrm}/k between younger and older rocks are determined in most instances by variations in the initial intensities, bulk susceptibilities being generally of the same order of magnitude for both the younger and older rocks. If the relative lack of magnetic intensity in the older rocks were due to the distruction of the primary magnetization through chemical changes in the magnetic mineralogy of the specimens, then this should be reflected in lower mean bulk susceptibilities for the older sites. Most of the specimens tested carry abundant phenocrysts and microphenocrysts of magnetite. The combined data suggest that the relative lack of a stable magnetic component in many of the older rocks is due to decay of the primary magnetization with time without the build-up of substantial components of secondary magnetization(s). One might also expect to see more of a tendancy for older specimens to acquire a magnetization in the sense and direction of the present or recent field. As can be seen in Figure 34, this effect was not observed.

Comparison with Other Results

Sixty-one paleomagnetic results in Genozoic rocks of North Pacific tectonic belts, including the results of the present study, have been compiled and are listed in Appendix II of this report. An attempt was made to select only those results which fulfill minimum criteria of magnetic stability. The results are displayed as paleomagnetic pole positions in Figures 39-42.

Quaternary and Plio-Pleistocene Results. (Fig. 39). The majority of the North American poles are derived from lavas of the Aleutian arc system. These have maximum error limits which include the geographic pole but not the present dipole field axis. The result derived from the Adagdak and Andrew lavas on Adak Island (pole no. 7), is consistent with the other Aleutian data.

Results from Kamchatka form a field which includes the present dipole field axis but not the geographic pole. The amount of overlap with the North American group is small, and by inspection it is concluded that the error limits of the means of the two groups do not overlap. Since the results are few, especially from Kamchatka, the significance of the seperation is uncertain at this time. In view of the very young ages of the rocks involved, it is very doubtful that the seperation is due to large scale tectonic causes unless the rates of ocean floor spreading and absolute continental displacements are much greater than previously supposed. Other tectonic mechanisms, such as a regional westward tilting of the Kamchatka-Kuriles crustal block, could possibly cause the seperation in pole positions however this author could find no evidence of even the possibility of such an occurrence in the Kamchatka-Kuriles area. Two of the five pole positions listed for the Kamchatka area are derived from Recent rocks. Only one of the five is listed as of definite Pleistocene age, and two are simply listed as Quaternary. Since most of the North American poles are derived from

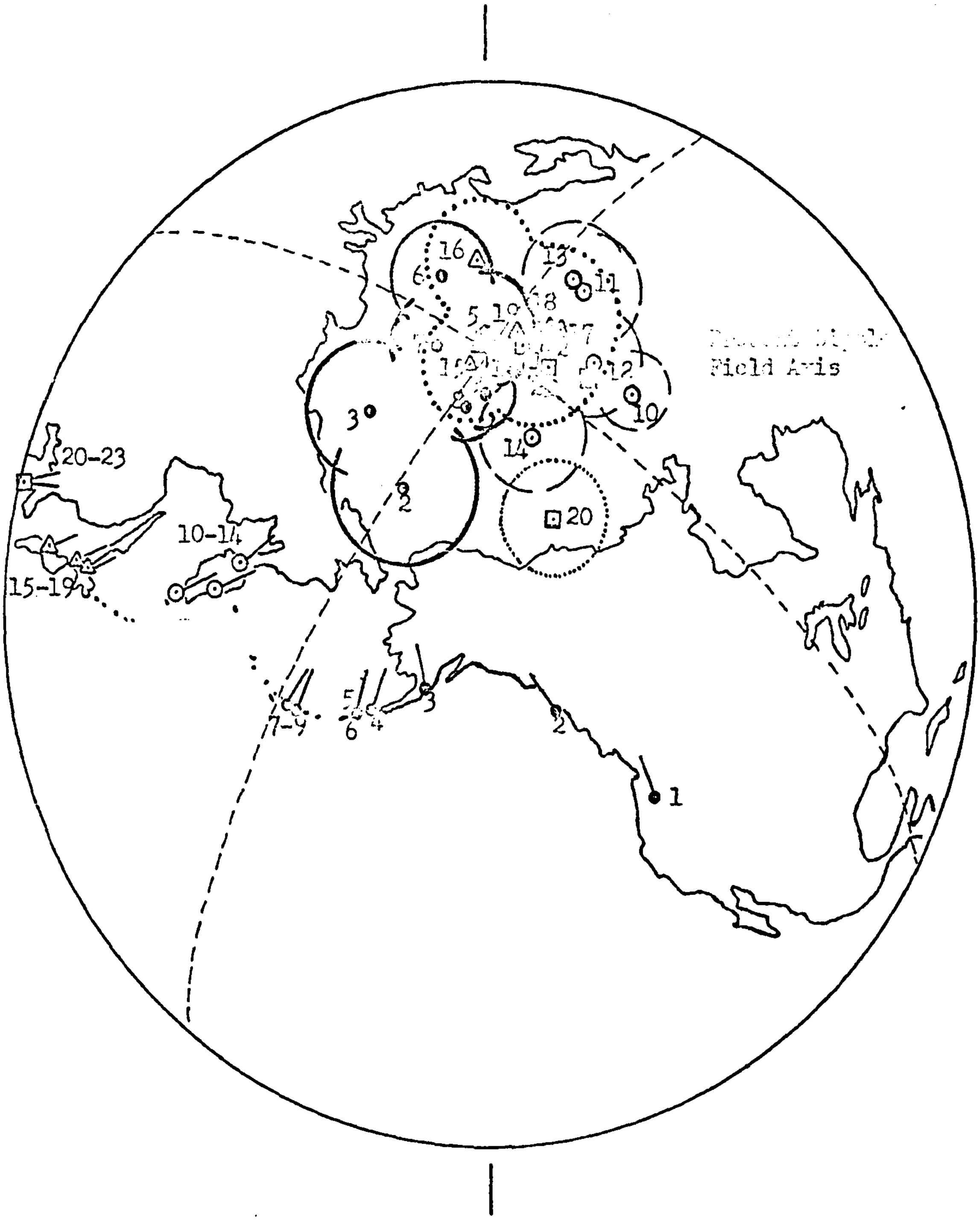


Figure 39. Quaternary and Plio-Pleistocene pole positions for North Pacific tectonic belts. Maximum error round North American poles shown by heavy solid line; round Kamchatka results by light dashed line; round Japanese and Formosian data by dotted line. Paleomagnetic declinations drawn at each site are approximate. Individual poles and sites numbered as in Appendix II.

Pleistocene and Plio-Pleistocene sequences, it is possible that the Kamchatka results reflect slightly younger Quaternary fields. It should be noted here that the number of North American sites is sufficiently large that the effect of secular variation on the results is minimal. The mean Pleistocene pole for Aleutian sites at 86.5 N, 153 E, is therefore probably a true reflection of the pleistocene pole position and not a 'spot reading' of the ancient field, (D. B. Stone, personal communication). Kamchatka data may possibly be too few in number to have meaned out the full effect of secular variation on the results. However, their consistant seperation from the North American results probably indicates that they reflect a slightly different Quaternary field than the one defined by the American results.

Results from Japan and Taiwan group betweem tje American and Kamchatka data. The maximum error limits of the Japanese and Taiwan results include both the geographic pole and, just barely, the present dipole field axis.

Plio-Pleistocene and Pliocene Results, (Fig. 40). The high dispersion of paleomagnetic poles from North Pacific sites of Pliocene age is in marked contrast to results from Quaternary and Miocene sites in the same region. In

Chapter 4 of this report it was tenatively concluded that the dispersion of poles from the Andesite Domes on Adak Island was due to excursions of the Pliocene field about its mean position. This conclusion is supported by the results from other Pliocene sites in the North Pacific region. Diverse directions in rocks of approximately the same age from the same general area occur in volcanics of the Lousetown Formation,

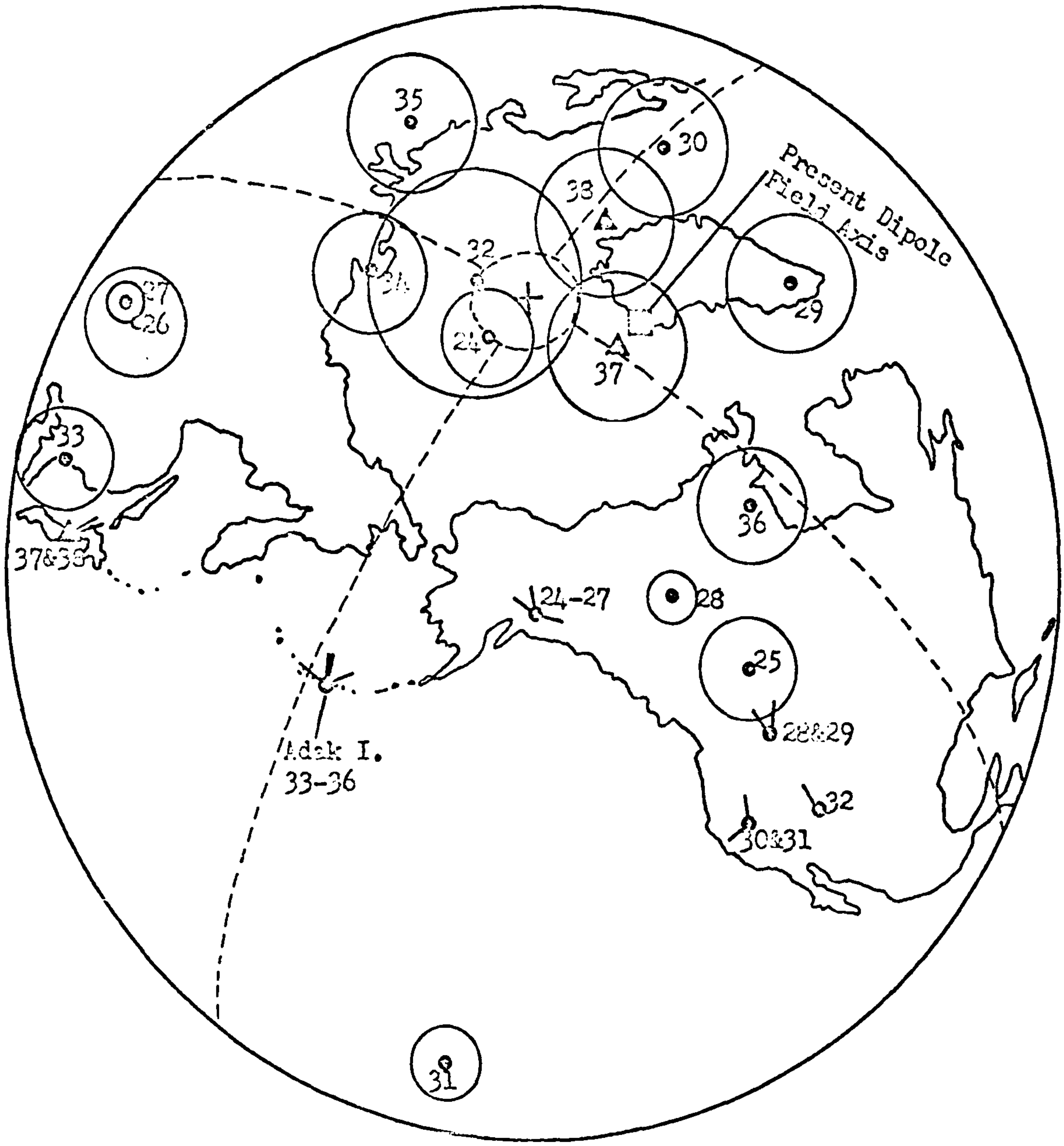


Figure 40. Pliocene and Plio-Pleistocene pole positions for North Pacific tectonic belts. Paleomagnetic declinations drawn at each site are approximate. Individual poles and sites numbered as in Appendix II.

(Nos. 30, 1.1-1.9m.y., and 31, 6,8 m.y.), Montana volcanics and sediments (Nos. 28 and 29); Lavas from the Wrangell mountains, (Nos. 24-27, 6.5 m.y.), and in intrusive andesites from the Andesite Domes on Adak Island, (Nos. 33-36, 3 m.y.). Most of these sites yield pole positions which have relatively small circles of confidence and their remanent magnetization appears to be substantially stable.

In the case of the Wrangell lavas and the Adak andesite intrusives, the intensity of the remanence is relatively high, indicating perhaps that the dispersion of their pole positions is not due to their being magnetized during polarity transition periods, when the strength of the main field is thought to be drastically attenuated. On the other hand, rocks from the Lousetown Volcanics exhibit mixed polarities indicating that they might have been formed during a main field polarity reversal.

However, at the present time the most that can be said from the standpoint of the existing data, is that pole positions from North Pacific area Pliocene sites have a higher dispersion than would normally be expected for rocks of this age. The data further suggests that this effect is the result of two phenomena which can be very closely associated in time:

1. Larger than normal field excursions occurring during the formation of the rocks.

2. Formation of some rock units during polarity transition periods when the strength of the main field is drastically reduced and the secular variation field is dominant.

Plio-Miocene and Miocene Results, (Fig. 41). Paleomagnetic pole positions from North America, Eastern USSR and Taiwan form a highly coherent group-

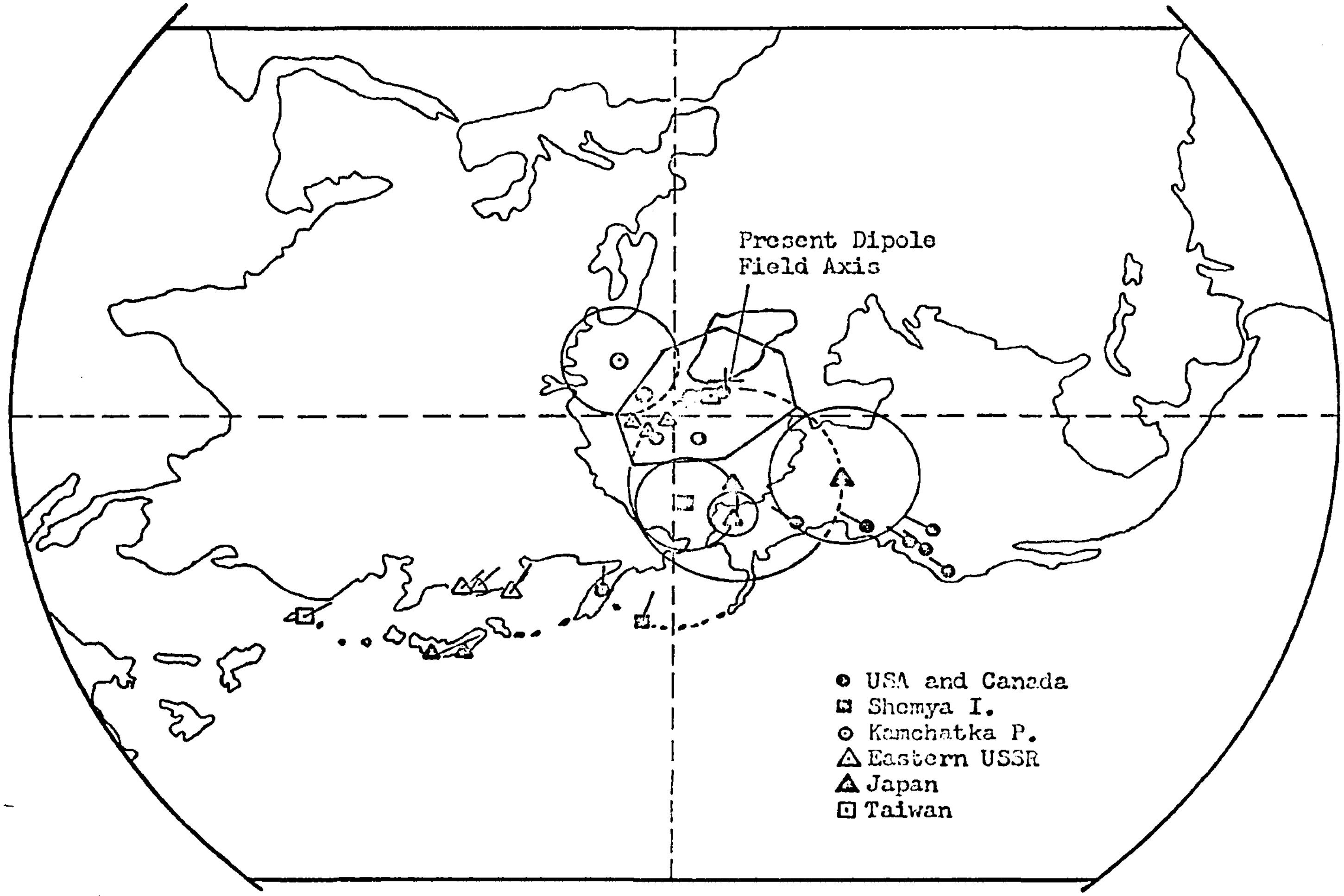


Figure 41. Miocene and Plio-Miocene sites and pole positions for North Pacific tectonic belts. Individual poles and sites listed in Appendix II.

ing which surrounds the geographic pole. The maximum error limits, outlined by the polygon, also includes the present dipole field axis. However, it is doubtful whether the error limits round the mean of these data would include the dipole axis.

Pole positions for Shemya Island, Kamchatka, and Japan are displaced from the American group. The circle of confidence round the mean pole position of the combined Japanese results (No. 49), substantially overlaps both the North American results and the pole for Shemya Island. Hence, these results are not significantly different at the 95% level of confidence. However it should be noted that the pole position for Upper Miocene rocks from Japan, (No. 48, shown with a very small circle of confidence in Figure 41), while significantly different from the pole positions of conterminous North America, Eastern USSR, and Taiwan, does not differ significantly from the pole position determined for Upper Miocene rocks on Shemya Island.

Pole positions derived from Miocene rocks on Shemya and Kamchatka differ significantly from each other and from the grouping formed by North American, Eastern USSR and Taiwan results. Miocene data from the Aleutian arc and the Kurile-Kamchatka area are as yet too few to determine whether the divergences are due to tectonic displacements, or simply reflect Miocene field excursions. However, in view of recent proposals which suggest the possibility of sea floor spreading directly behind island arcs in such places as the Seas of Japan and Okhotsk, it is perhaps quite significant that the mean declinations of remanent magnetization from Kamchatka and Eastern USSR differ by some 18-20°. Rotation of the Kamchatka Peninsula by this amount in a clockwise sense about an axis located in the northernmost reaches of the Shelekhova Gulf, (northern Sea of Okhotsk)

1. Effectively 'closes' the major portion of the Sea of Okhotsk.

2. Brings the mean direction of magnetization from Kamchatka into good agreement with those from Eastern USSR and Taiwan.

3. The pole position for Kamchatka is shifted by this rotation into the grouping of poles outlined by the polygon in Figure 41.

The paleolatitude derived from the remanent magnetization of the Shemya Miocene rocks (approximately 69° N) is too high to be fully explained by such mechanisms as sea-floor spreading. In view of the complex tectonic history of the Aleutian arc, it is just possible that tilting of the Near Islands Platform may have occurred since the Miocene. This could affect the mean direction of magnetization especially the inclination.

However, it must be emphasized that the Miocene data are too few from the Aleutian arc and Kamchatka-Kurile to place much faith at this point in the highly speculative arguments outlined above. The divergences in the Miocene results might just as well be due to excursions of the main dipole field about its mean position during the Miocene.

Paleogene Results, (Figure 42).

Only a limited number of Eocene and Oligocene results were available for sites in the North Pacific tectonic Belts. Of these Irving (1964(considers some to be non-representative of Paleogene fields. He reports the possibility that secular variation and tectonic rotation are likely to have affected the direction of remanent magnetization of the

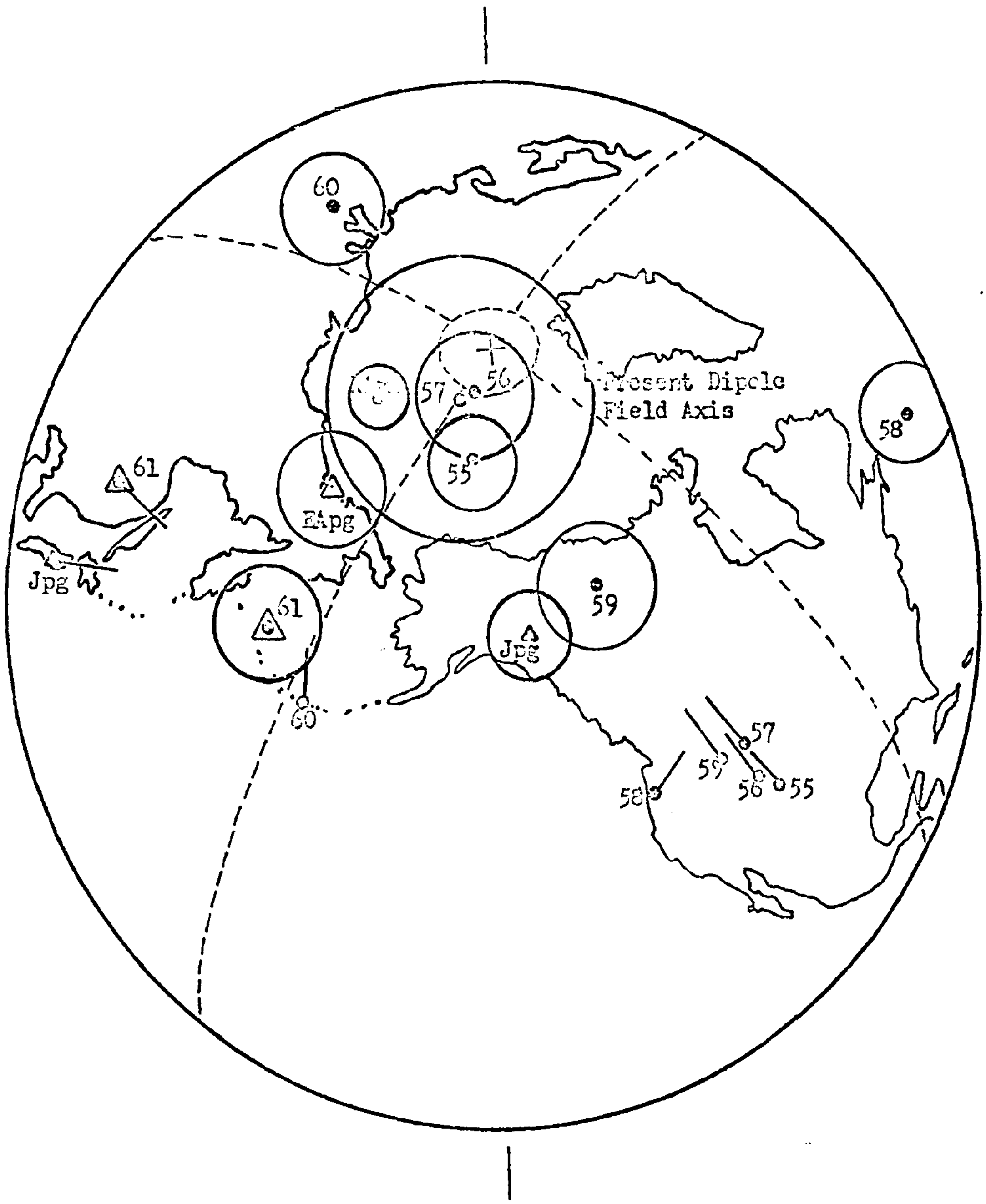


Figure 42. Paleogene pole positions from sites in Western United States and North Pacific tectonic belts. Paleomagnetic declinations drawn at each site are approximate. Individual poles and sites numbered as in Appendix II with the exception of mean Japanese Paleogene pole (Jpg), Erasian paleogene pole (EApg), and North American Mid-Tertiary pole (NAmt)

Siletz Volcanics (No. 58). He also feels that the result from the Wasatch Formation (No. 57), is based on too few samples to be meaningful. Unlike most eocene poles from Europe and Northern Asia, result No. 56 from part of the Green River Formation in Colorado, (No. 56), includes the geographic pole. On this basis Irving (1964) considers the result questionable.

If Irving's analyses of the available data are correct then only the results from the Finger Bay Volcanics and part of the Green River Formation, (No. 55), can be used as Eocene pole positions, and as has already been indicated the result from Adak must be treated with caution.

Unpublished mean Paleogene poles for Japan (Jpg) and Eurasia (EApg), as well as a mean Mid-Tertiary pole position for North America (NAmt) are as quoted at the U. S. - Japan Paleomagnetic Conference in Hawaii, February, 1970. These pole positions are significantly different from each other at the 95% confidence level. Since paleomagnetic evidence indicates that oroclinal bending of the Japanese Archepelago took place during the Early Tertiary, it is probable that the Paleogene pole position has been affected by tectonic activity, especially if the pole position is partially based on results from rocks in the fossa magna zone (Irving, 1964).

The result from the Finger Bay volcanics is well displaced from the other pole positions and from both the geographic pole and the present dipole field axis. However, until more experimental information is available regarding the magnetic stability of the Finger Bay Volcanics, and the variation in ages within the section, and until such time as results from other Early Tertiary sites in the North Pacific are available, the significance of the pole position derived in the course of the present study will remain uncertain.

Suggestions for Future Work

1. The paleomagnetic laboratory at the University of Alaska has only recently achieved capability in the area of thermal demagnetization. An attempt should be made to isolate the TRM component, if present, in the igneous units of the Finger Bay Volcanics. Thermal demagnetization studies should be applied in all such cases where there is some real doubt as to the nature and stability of the remanent magnetization.

2. Such studies are aided by careful examinations of the opaque mineralogy of the samples in question. While the degree to which a given investigator might wish to involve himself in such persuits varies with the purpose of the investigation being conducted, it is suggested that information gained with the petrographic microscope might save time overall and help in the interpretation applied to the paleomagnetic results. With this in mind, and from the basis of his own experience, the writer suggests that polished thin sections be used for the petrographic examination of the specimens rather than standard thin sections. The polished sections, when prepared commercially are more expensive but are well worth the cost in view of their added versatility in terms of the examination of the opaque mineralogy. It is thought that at least one polished section per site should be prepared (providing that only one lithology is present at the site) and studied from the standpoint of the opaque mineralogy.

3. X-ray diffraction studies would probably prove helpful in determining the extent of sub-solidus oxidation in magnetite phases.

4. The attempt to effectively isolate stable TRM components in weak, altered sections such as the Finger Bay Volcanics will require a more sensitive magnetometer. Until such time as the project has a magnetometer with effective sensitivity of 10^{-7}-10^{-8} emu/cc, (which would probably give an absolute sensitivity of 10^{-8}-10^{-9} emu/cc), it is not recommended that any further work be attempted with rocks of the early marine series from the Aleutian Arc. When a more sensitive magnetometer becomes available it is suggested that the study of the older rocks be extended to include sections of the early marine series in Atka and in the Near Islands.

5. A more rigorous search of the literature than has been possible to conduct during the course of this study should be made in order to increase the number of pole positions from the tectonic belts bounding the North Pacific. A search for Russian and Chinese data might especially prove useful.

APPENDIX I

Paleomagnetic Data from the Margin of a Hypabyssal Andesite in the Western Aleutians, Alaska

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ABSTRACT

Paleomagnetic data used to establish the thermal nature of an andesite-sediment contact on Shemya Island are reported. The variations in the magnetic properties of the andesite appear to result from systematic increases in oxidation effects toward the contact.

1. INTRODUCTION

Five core specimens (S60-S64) were collected from a Mid-Late Miocene Hornblende Andesite Porphyry which is exposed in an abandoned quarry on the north side of Shemya Island, (Lat. 52 44.5'N, Long. 174 05.7'E), in the Near Island Group, Western Aleutian Islands. A well defined, steep west-dripping contact between the andesite and early Tertiary sediments which are highly sheared and deformed is exposed at the western edge of the quarry. Oriented core samples were collected at intervals of 1-5 meters with S64 taken nearest to the contact. It was not possible to collect samples of the sediments because of their sheared, broken, and weathered nature.

The usual field criteria used in defining igneous contact relations were found to be lacking, and as a result the mode of occurrence of the andesite and the nature of the contact were not clear. Since intrusives of the same age and apparent composition occur in fault contact with similar sediments at other localities on the island, it was initially assumed that the same situation prevailed at the quarry site.

2. PETROGRAPHY

Phenocrysts and microphenocrysts of zoned and unzoned plagioclase (An44), light green hornblende, oxyhornblende, clinopyroxene, hypersthene, opagque oxides, and uralite, are situated in a fine-grained, felted matrix composed of plagioclase, minor alkali feldspar, amphibole and pyroxene. Accessory minerals and alteration products include chlorite, uralite, epidote, quartz, carbonate, and Fe-oxides. Most of the mafic grains show the effect of hydrothermal alterations which affected both the phenocrysts and matrix of the rock.

3. MEASUREMENTS

Natural remanent magnetizations (NRM) of the specimens were measured using a fluxgate gradiometer magnetometer. The low field specific susceptibility of each specimen was also measured. Discs from each specimen were individually demagnetized in successive peak alternating fields of 50, 125, 250, 500, 1000 and 2000 oersteds. The remanence after each step was measured on a 5 c.p.s, spinner-type magnetometer (Foster, 1966).

4. RESULTS

The results of the measurements are summarized in figure 1 and table 1. This table shows:

1. A slight but systematic decrease in the susceptibility (k) with distance from the contact.

Table I-1 Remanence Directions of the Specimens during Stepwise AF Demagnetization

Specimen No.	S64			S63			S62			S61			S60		
Alternating Field (oe)	D	I	J_{rm}	D	I	J_{rm}	D	I	J_{rm}	D	I	J_{rm}	D	I	J_{rm}
NRM	3	69	22.9	26	77	25.0	347	77	23.2	358	78	29.7	353	73	32.2
250	352	80	3.4	13	75	3.4	23	78	9.8	357	74	11.9	352	76	16.4
500	319	64	0.8	318	50	1.1	40	77	6.6	354	75	7.2	347	75	8.7
1000	305	1	0.2	328	44	0.8	65	62	2.6	349	72	3.4	325	75	0.7
2000	284	-55	0.2	303	-2	0.3	179	36	0.4	290	63	0.6	339	67	0.7
Dist. from Contact (m)	$\sim$ 3 $\sim$			$\sim$ 5			$\sim$ 10			$\sim$ 13			$\sim$ 14		
k ($\times 10^{-3}$ emu/cm^3)	3.54			3.50			3.47			3.06			2.98		

D, declination of remanent magnetization (°)
I, inclination of remanent magnetization (°)
J_{rm}, intensity of remanent magnetization ($\times 10^{-4}$ emu/cm^3)
k, susceptibility ($\times 10^{-3}$ emu/cm^3)

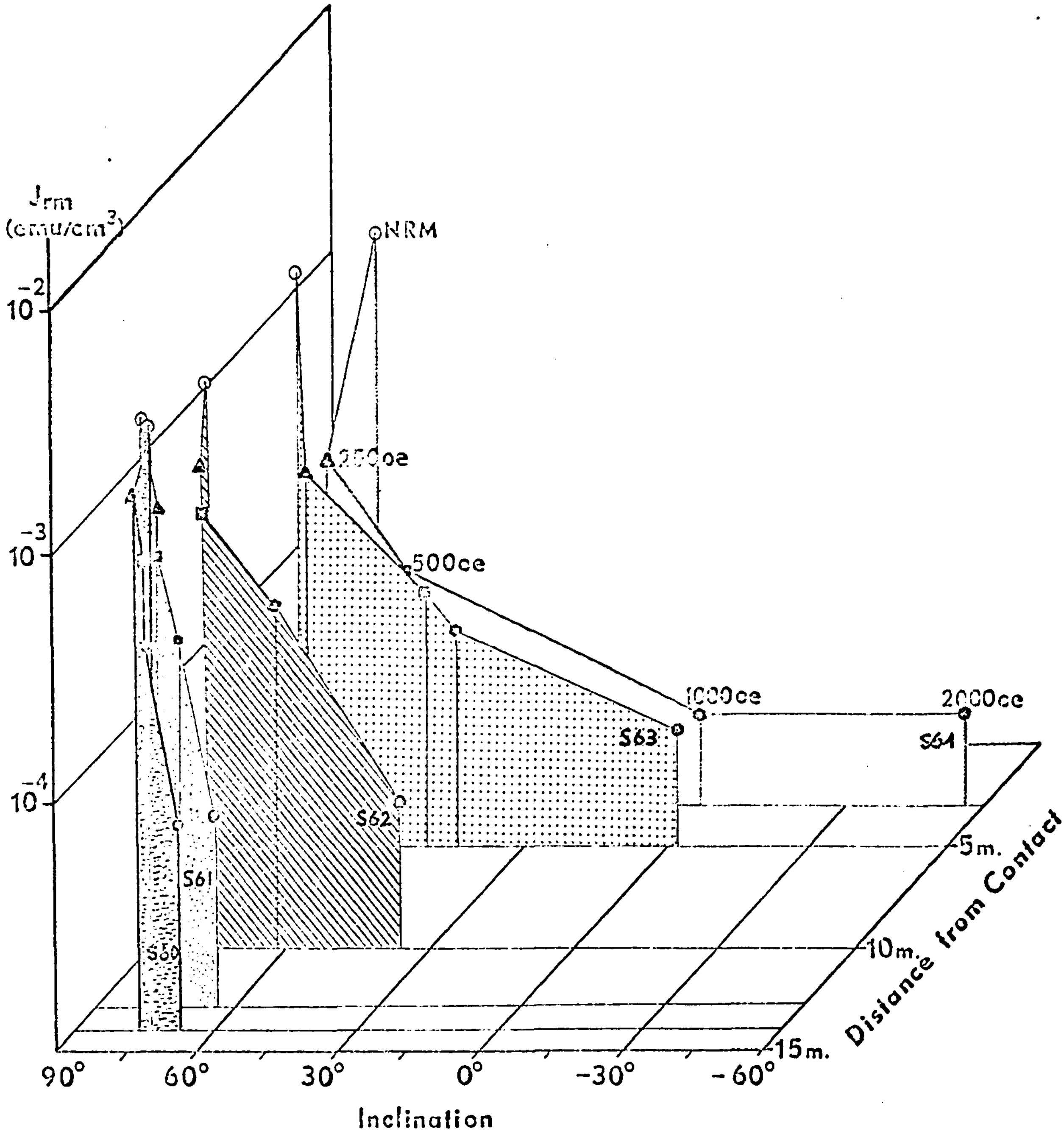

Figure I-1. Behavior of site parameters as a function of distance from the contact, and increasing alternating field.

2. An increase in the intensity of the NRM (J_{rm}), with distance from the contact.
3. That the relative intensities of magnetization after AF demagnetization at any given peak field increases with distance from the contact. This is interpreted as being due to systematic compositional, and hence coercivity differences in the magnetic mineral fractions of the specimens.
4. That with increasing peak alternating fields there is a systematic westward rotation of the directions and a shallowing of the inclinations (with the exception of S62, where the direction rotates to the east). This effect diminishes with distance from the contact.

5. STUDY OF POLISHED THIN SECTIONS

In an attempt to find reasons for the above variations, polished thin sections of the specimens in vertical reflected light were studied. The magnetic oxides of the specimens exist in two distinct phases--as relatively large grains of primary titanomagnetite, and as very fine, interstitial aggregates of titanomaghemite and rare limonite. The former was observed to vary little in character and abundance, although there appears to be a slight decrease in the amount of large titanomagnetite grains with distance from the contact. The primary titanomagnetite is for the most part unaltered and only minor occurrences of exsolution lamellae were observed. On the other hand, the frequency of occurrence of titanomaghemite and limonite increases toward the contact. This increase is associated with a higher degree of oxidation of the mafic minerals, especially in the matrix, as the contact is approached. It was also noted that the sections became noticeably darker colored toward the contact.

6. CONCLUSIONS

A solution to the problem as originally stated can be deduced solely from consideration of the behavior of the remanent magnetizations in high alternating fields. The systematic variations in magnetic properties are most easily explained in terms of an intrusive phenomena. The oxidation of primary hornblende and pyroxenes commenced with the rapid release of pressure due to mobilization of the melt and its emplacement at a higher level in the crust. The continued alteration of these phases as well as the creation of titanomaghemite phases was probably enhanced by a water gradient between the host sediment and the intruding melt which favored oxidation reactions in the andesite. The effects of these late stage alterations diminish with distance from the contact.

The systematic rotations of the remanent directions with increasing peak fields, and the attenuation of this effect with distance from the contact is more difficult to account for, but it may be due to local disturbance of the original geomagnetic field by the intrusion. Perhaps if more samples had been available, especially from the sedimentary side of the contact, it might have been possible to determine the origin of this direction change exactly. However, it is felt that the results are sufficiently consistent to justify the conclusions drawn here.

ACKNOWLEDGEMENTS

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APPENDIX II

REFERENCE LIST OF TERTIARY AND QUATERNARY PALEOMAGNETIC DIRECTIONS AND POLE POSITIONS FOR NORTH PACIFIC TECTONIC BELTS

Explanation of Tables

Column 1 gives the map reference number of the pole as displayed in Chapter 5, Figures 39-42.

Column 2 gives the location of the rock unit(s) by country and geographic coordinates. Mean geographical coordinates are given in those cases where many results over a large area have been combined.

Column 3 gives the name of the rock units studied and in some cases specific locations, mode of occurrence, and number of sites, units, samples and/or specimens examined. The population used for the computation of the mean results is given by N.

Column 4 gives the relative age of the rock unit studied. The geological age is specified by the following symbols: Quaternary Q, subdivided where possible into Recent Qr, and Pleistocene Qp; Tertiary T, subdivided into epochs Pliocene Tp, Miocene Tm, Oligocene To, and Eocene Te.

Column 5, 6 and 7 give the estimated direction of magnetization by Declination D_m, in degrees east of true north and Inclination I_m, in degrees down from the horizontal plane at the time of the magnetization of the rock. The estimated error in the mean direction is given by $\alpha 95$, the half-angle of the cone whose axis is the mean direction D_m, I_m.

Column 8 gives the polarity of the mean direction of the magnetization N= normal, R = reversed, M = mixed.

Columns 9, 10 and 11 give the coordinates of the paleomagnetic pole. Estimates of the error in the pole position are given by (δm,δp), the semi-axes of the elliptical error area round the pole at a probability of 95%.

Column 12 gives the reference from which the results were taken. These references are numbered as follows:

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Reference List of Tertiary and Quaternary Paleomagnetic Directions and Pole Positions for North Pacific Tectonic Belts

Map Ref. No.	Location	Rock Unit Studied Name	Age	Directions of Magnetization D_m	I_m	α 95	Polarity	Paleomagnetic Pole Lat (°N)	Long (°E)	(δm δp)	Ref.
QUATERNARY (LESS THAN 1 M. Y.) AND PLIO-PLEISTOCENE											
1	USA (44N , 122W)	Suttle Lake Lavas Oregon, 19 Flows, (N = 19) (	Q	178	61	6.3	R	88	272	(8, 9)	(6)
2	USA (62N , 143W)	Mt. Edgecumbe Lavas, SE Alaska, 5 Flows, (N = 5)	Q	335	78	7.6	N	75	183	(14,14)	(7)
3	USA (58N , 155W)	Mt. Griggs Volcanics Alaska Peninsula, 5 Flows, (N - 5)	Q	336	77	7.2	N	77	151	(13, 13)	(7)
4	USA (54N , 167W)	Driftwood Bay Lavas, Unalaska I., 20 Flows, (N = 20)	Q	1	69	3.3	N	89	351	(5, 6)	(7)
5	USA (53N , 168W)	Crater Creek Basalts Umnak I., 15 Flows, (N - 15)	Q	358	67	5.1	N	86	32	(7, 8)	(7)

Reference List of Tertiary and Quaternary Paleomagnetic Directions and Pole Positions for North Pacific Tectonic Belts

Map Ref. No.	Location	Rock Unit Studied Name	Age	Directions of Magnetization D_m	I_m	α_{95}	Polarity	Paleomagnetic Pole Lat (°N)	Long (°E)	(δm, δp)	Ref.
QUATERNARY (LESS THAN 1 M. Y.) AND PLIO-PLEISTOCENE (Continued)											
6	USA (53N , 168W)	New Jersey Creek Lavas, Umnak I., 19 Flows, (N = 19)	Q	348	65	4.0	N	80	66	(5, 6)	(7)
7	USA (52N , 177W)	Adagdak and Andrews Lavas, Adak I., 61 specimens, (N =61)	Qp	352	70	3.3	N	85	115	(5, 6)	(1)
8	USA (52N , 177W)	Round Head Basalts, Kanaga I., 14 Flows (N = 14)	Qp	2	72	2.0	N	85	189	(3, 3)	(7)
9	USA (52N , 177W)	Kanaton Basalts, Kanaga I., 52 specimens, (N =52)	Qp	355	65	2.9	N	84	216	(4, 5)	(7)
10	USSR (53N,159E)	Kamchatka Andesite-Basalts, 19 samples, (N = 19)	Q	15	61	3.0	N	75	291	(3, 5)	(2)

Reference List of Tertiary and Quaternary Paleomagnetic Directions and Pole Positions for North Pacific Tectonic Belts

Map Ref. No.	Location	Rock Unit Studied Name	Age	Directions of Magnetization D_m	I_m	α 95	Polarity	Paleomagnetic Pole Lat (°N)	Long (°E)	(δm,δp)	Ref.
QUATERNARY (LESS THAN L M. Y.) AND PLIO-PLEISTOCENE (Continued)											
11	USSR (57N , 161E)	Sheveluch, (Kamchatka Volcanic Domes, 17 samples, (N = 17)	Qr	4	62	6.0	N	77	340	(7, 9)	(2)
12	USSR (49N , 154E)	Kurile Is., Lavas, 7 samples, (N = 7)	Q	345	65	5.0	N	80	296	(5, 7)	(2)
13	USSR (57N , 161E)	Kurile Is., Andesites	Qr	3	61	6.0	R	77	346	(6, 8	(3)
14	USSR (49N, 154E)	Kurile Is., Basalts and Andesites	Qp	15	65	5.0	R	80	245	(7, 8)	(3)
15	Japan (35N,132E)	Yamaguchi Basalt, 85 sites, 300 samples, 650 specimens, (N=85)	Qp	0	57	4.0	M	87	132	(4, 6)	(2)
16	Japan (35N,139E)	North Izu and Hakone Rocks, 42 flows, 300 samples, (N=42)	Qp-r	343	51	7.0	M	78	46	(7, 7)	(2)
17	Japan (36N,138E)	Quaternary Volcanic Rocks, 11 flows, (N = 11)	Q	359	47	11.0	N	83	325	(10,15)	(2)

Reference list of Tertiary and Quaternary Paleomagnetic Directions and Pole Positions for North Pacific Tectonic Belts

Map Ref. No.	Location	Rock Unit Studied: Name	Age	Directions of Magnetization: D_m	I_m	α_{95}	Polarity	Paleomagnetic Pole: Lat (°N)	Long (°E)	(δm δp)	Ref.
QUATERNARY (LESS THAN 1 M. Y.) AND PLIO-PLEISTOCENE											
18	Japan (38N,140E)	Lavas, 12 flows, (N=12), data corrected to Tokyo	Qr	357	46	4.0	N	82	335	(4,6)	(2)
19	Japan (38N,140E)	Archeological Baked Clays, 174 sets, data corrected to Tokyo	Qr	356	53	5.0	N	86	341	(3,4)	(2)
20	Taiwan (25N, 122E)	Keelung Volcano Group 32 sites, 79 specimens (N~79)	Qp	16	31	8.0	M	73	238	(5,9)	(5)
21	Taiwan (25N, 122E)	Tatun Volcano Group 36 sites, 161 specimens, (N=161)	Tp-Qp	3	36	5.0	N	84	275	(4,6)	(5)
22	Taiwan (24N, 120E)	Penglin Islands Basalt, 14 sites 165 specimens, (N=165)	Tp-Qp	3	35	9.0	M	85	271	(6,10)	(5)
23	Taiwan (24N,121E)	Shiukuran River Andesites, 14 sites, 69 specimens (N=69)	Tp-Qp	1	33	9.0	N	86	283	(6,10)	(5)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

Map Ref. No.	Rock Unit Studied: Location	Name	Age	Direction of Magnetization: D_m	I_m	α_{95}	Paleomagnetic Pole: Polarity	Lat. (°N)	Long (°E)	(δm δp)	Ref.
Plio-Pleistocene and Pliocene											
24	USA (62N,143W)	Wrangell Volcanics, 9 flows, (N=9)	Tp-Qp	35	77	3.1	N	85	173	(6,6)	(7)
25	USA (62N,143W)	Wrangell Volcanics, 11 flows, (N-11)	Tp-Qp	109	80	3.7	N	51	248	(f,f)	(7)
26	USA (62N,143W)	Wrangell Volcanics, 16 flows, (N-16)	Tp	305	56	6.3	N	48	115	(F,9)	(7)
27	USA (62N,143W)	Wrangell Volcanics, 9 flows, (N=9)	Tp	306	49	2.0	N	43	109	(2,3)	(7)
28	USA (45N,112W)	Volcanics and Sediments, Montana, 5 units, (N=5)	Tp-Qp	--	--	--	N	60	241	(13,13)	(5)
29	USA (46N, 112W)	Basalt flow, Montana, 12 samples (N=12)	Tp-Qp	--	--	--	R	64	294	(9,10)	(5)
30	USA (39N,120W)	Lousetown Formation Volcanics, 23 flows, (N=23)	Tp-Qp	23	45	8.0	M	67	357	(7,11)	(5)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

	Rock Unit Studied			Direction of Magnetization			Paleomagnetic Pole				
Map Ref. No.	Location	Name	Age	D_m	I_m	α_{95}	Polarity	Lat. (°N)	Long. (°E)	($\delta m, \delta p$)	Ref.
PLIO-PLEISTOCENE AND PLIOCENE											
31	USA (39N,120W)	Lousetown Formation Volcanics, 32 flows (N=32)	Tp	64	-67	2.0	M	16	204	(3,4)	(5)
32	USA (35N,112W)	Lavas and Baked Sediments, New Mexico and Arizona, 24 sites (N=111)	Tp	177	-51	10.0	M	85	109	(10,14)	(5)
33	USA (52N,177W)	Andesite Dome, Adak I., (N=12)	Tp	89	-66	6.2	R	35	128	(8,10)	(1)
34	USA (52N,177W)	Andesite Dome, Adak I., (N=10)	Tp	335	70	4.6	N	75	110	(7,8)	(1)
35	USA (52N,177W)	Andesite Dome, Adak I., (N=7)	Tp	153	-53	12.9	R	63	60	(13,18)	(1))
36	USA (52N,177W)	Andesite Dome, Adak I., (N=8)	Tp	223	-68	6.0	R	64	259	(8,9)	(1)
37	Japan (36N,138E)	Combined Pliocene Lavas, (N=4)	Tp	--	--	--	M	80	271	(10,10)	(2)
38	Japan (36N,138E)	Enrei Formation Combined, (N=27)	Tp	172	-43	10.0	R	77	352	(8,13)	(2)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

Rock Unit Studied				Direction of Magnetization				Paleomagnetic Pole			
Map Ref. No.	Location	Name	Age	D_m	I_m	α_{95}	Polarity	Lat (°N)	Long. (°E)	($\delta m, \delta p$)	Ref.
PLIO-MIOCENE AND MIOCENE (NEOGENE)											
39	USA (38N,122W)	Nelroy Formation, (N=29)	Tm	7	58	3.0	N	85	318	(3,4)	(2)
40	USA (43N,115W)	Payette Formation (N=13)	Tm	1	62	3.0	N	89	316	(3,5)	(2)
41	USA (46N,120W)	Ellensberg Formation, (N=23)	Tm-Tp	1	69	9.0	N	85	245	(13,15)	(2)
42	USA (47N,121W)	Columbia River Basalts, 114 flows, (N=11)	Tm	7	65	9.0	M	85	317	(9,14)	(2)
43	USA (43N,120W)	Albert Rim Lavas, 16 flows, (N=98)	Tm	180	-52	5.0	R	80	62	(6,6)	(4)
44	Canada (52N,121W)	Cariboo Basalts, 49 flows, (N=49)	Tm	--	--	--	-	84	220	(5,5)	(8)
45	Canada (61N,134W)	Tertiary Basalts, 46 samples, (N=46)	Tm-.	349	75	4.0	M	85	150	(5,6)	(2)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

Rock Unit Studied				Direction of Magnetization				Paleomagnetic Pole			
Map Ref. No.	Location	Name	Age	D_m	I_m	α 95	Polarity	Lat. (°N)	Long. (°E)	(δm, δp)	Ref.
PLIO-MIOCENE AND MIOCENE (NEOGENE)											
46	USA (53N,174E)	Shemya Andesite and Basalts, 7 sites, 56 specimens, (N=7)	Tm	11	79	5.0	M	73	189	(9,9)	(1)
47	USSR (55N,160E)	Kamchatka Rocks Combined	Tm-Tp	342	65	--	N	76	43	(10,10)	(2)
48	Japan	Miocene Igneous Rocks (upper)(N=32)	Tm	27	59	3.0	M	68	208	(4,5)	(2)
48	Japan	Miocene Igneous Rocks (Lower)(N=20)	Tm	32	40	11.0	M	59	247	(8,13)	(2)
49	Japan	Miocene Igneous Rocks Combined (N=7)	Tm	--	--	--	-	73	216	(22,22)	(2)
50	Taiwan (25N,121E)	Chiapanshan Area Basalts, 10 sites,(N=67)	Tm	1	31	13.0	M	82	294	(8,14)	(5)
51	Taiwan (24N,121E)	Shiukuran River Andesites, 4 sites,(N=15)	Tm	182	-25	16.0	R	80	293	(10,18)	(5)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

Rock Unit Studied				Direction of Magnetization				Paleomagnetic Pole			
Map Ref. No.	Location	Name	Age	D_m	I_m	$\alpha 95$	Polarity	Lat. (°N)	Long. (°E)	$(\delta m, \delta p)$	Ref.
PLIO-MIOCENE AND MIOCENE (NEOGENE), (Continued)											
52	USSR (49N,145E)	Khaborovsk Basalt, (N=110)	Tm-Tp	7	66	5.0	M	85	232	(9,9)	(2)
53	USSR (43N,131E)	Primore Basalts, (N=280?)	Tm-Tp	0	64	5.0	M	89	131	(7,8)	(2)
54	USSR (49N,141E)	Sakhalin Basalts, (N=102?)	Tp	352	70	3.0	M	83	100	(4,5)	(2)
PALEOGENE (63 - 27M. Y.)											
55	USA (40N,108W)	Green River Formation, (N=7)	Te	345	65	5.0	N	78	202	(6,7)	(2)
56	USA (42N,110W)	Green River Formation (N=19)	Te	355	63	6.0	N	85	192	(8,9)	(2)
57	USA (45N,109W)	Wasatch Formation (N=4)	Te	351	64	17.0	N	84	180	(20,27)	(2)
58	USA (45N,124W)	Siletz River Volcanics (N=8)	Te	70	55	7.0	M	37	211	(7,10)	(2)

Reference List of Paleomagnetic Directions and Pole Positions (Continued)

Rock Unit Studied				Direction of Magnetization				Paleomagnetic Pole			
Map Ref.No.	Location	Name	Age	D_m	I_m	α_{95}	Polarity	Lat. (°N)	Long. (°E)	($\delta m,\delta p$)	Ref.
59	USA (45N,113W)	Beaverhead Valley Volcanics, 4 flows (N=4)	Te	--	--	--	N	66	239	(10,11)	(5)
60	USA (52N,177W)	Finger Bay Volcanics Adak I., 5 sites, 77 specimens, (N=77)	Te	326	56	9.2	M	61	74	(10,13)	(1)
61	USSR (44N,132E)	Primore Basalts,	To	52	76	5.0	M	55	172	(9,9)	(2)

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